Solar-Protective Glazing for Cold Climates

A Parametric Study of Energy Use in Offices

Marie-Claude Dubois

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Keywords

Solar-protective glazing; energy use; reflective; heat-absorbing; tinted glass; offices; cold climates; heating; cooling; peak loads; indoor temperature.
Annual energy use for heating and cooling an office room equipped with various types of solar-protective glazings was studied with the aim of identifying the glazing optical properties that yield low energy use in cold climates. The room's orientation, the glazing-to-wall area ratio ($GWAR$) and the climate were alternately varied and the impact of these parameters on annual energy use, peak demand and indoor temperature was analysed. The study was carried out through computer simulations of energy use with the program DEROB-LTH, which uses angular-dependent calculation algorithms for windows. Specific heat losses, internal loads, ventilation, infiltration rates and temperature set points were kept constant for all cases and heating and cooling loads were added in a 1:1 ratio throughout the study. Results indicate that, in heating-dominated climates, solar-protective glazings reduce cooling loads significantly but increase the heating demand thus increasing annual energy use in most cases. On south and north facades, high solar transmittance glazing ($SC > 0.6$) yielded lower annual energy use than average transmittance glazing with 30% $GWAR$ because cooling loads were easily offset by large reductions in heating. On east and west facades, however, average transmittance glazing ($0.4 < SC < 0.6$) performed better than high transmittance glazing. A low-emissivity coated glazing ($SC = 0.6$) appeared to be a good solution for all orientations while extremely low solar transmittance glazing ($SC = 0.16$) was always a poor solution. South and north orientations had a lower annual energy use with a larger solar aperture than east and west facades indicating that larger glazing areas or a higher shading coefficient should be selected on south and north facades. A higher solar transmittance or larger glazing areas were also more energy-efficient in Montreal and Luleå than in Lund, Stockholm and Oslo because there is a larger potential for passive solar utilisation in the winter in those cities. In general, it was found that the orientation and glazing solar transmittance affected heating loads in the same way while the effect of glazing transmittance on cooling loads was more significant than that of orientation. The study generally indicates that solar-protective
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glazing with an average $SC$ can be energy-efficient in cold climates provided that an appropriate glazing area is selected and that the orientation and climate are taken into consideration in the design.
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Nomenclature

$A_{frame}$  Frame area  $(m^2)$
$A_{glazing}$  Glazing area  $(m^2)$
$A_i$  Surface area of the building component $i$  $(m^2)$
$A_{om}$  Aggregate area of the surfaces  $(m^2)$
$A_{wall}$  Area of the opaque wall  $(m^2)$
$C_{og}$  Centre of glass  (-)
$COP$  Coefficient of performance  (-)
$E_i$  Solar irradiance  $(W/m^2)$
$GWAR$  Glazing-to-wall area ratio  (%)  
$N_i$  Inward flowing fraction of absorbed energy  (-)
$q_i$  Total solar gain  $(W/m^2)$
$q_{rad}$  Radiated energy  $(W/m^2)$
R.H.  Relative humidity  (%)  
$SA$  Solar aperture  (-)
$SC$  Shading coefficient  (-)
$SHGC$  Solar heat gain coefficient  (-)
$T$  Temperature  (K)
$U_m$  Average thermal transmittance  $(W/m^2K)$
$U_i$  Thermal transmittance of the building component $i$  $(W/m^2K)$
$\alpha(\lambda)$  Absorptance as a function of wavelength $\lambda$  (%)  
$\alpha_s$  Glazing solar absorptance  ( %)
$\varepsilon$  Emittance  ( %)
$\kappa$  Conductivity  $(W/m°C)$
$\lambda$  Wavelength  ($\mu$m)
$\theta$  Angle of incidence on window pane  (°)
$\rho(\lambda)$  Reflectance as a function of wavelength $\lambda$  ( %)
$\rho_s$  Glazing solar reflectance  ( %)
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<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
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<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann constant</td>
<td>(W/K$^4$m$^2$)</td>
</tr>
<tr>
<td>$\tau(\lambda)$</td>
<td>Transmittance as a function of wavelength $\lambda$</td>
<td>(%)</td>
</tr>
<tr>
<td>$\tau_s$</td>
<td>Glazing solar transmittance</td>
<td>(%)</td>
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<td>$\tau_v$</td>
<td>Glazing visual transmittance</td>
<td>(%)</td>
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<tr>
<td>$\perp$</td>
<td>Normal incidence</td>
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Solar-Protective Glazing for Cold Climates
1 Introduction

1.1 Why save energy?

The reasons for being concerned about the issue of energy were traditionally related to its cost, the local pollution due to energy production and the security of energy supply (NAPAG, 1995). Today, the capacity to expand energy supply at low cost and environmental burdens connected with energy use have started to weigh more in the balance (Schipper et al., 1992). Environmental impacts that have attracted most attention from policy makers in recent years are atmospheric–global warming and acid rain–both of which stem largely from the combustion of fossil fuels (Stanners & Bourdeau, 1995).

Although there was much controversy about the global warming issue at the beginning of the 1990’s (Mannion & Bowlby, 1992), recent analyses report that the continued accumulation of greenhouse gases in the atmosphere is in fact leading to measurable climatic change (IPCC, 1995 in Wiel et al., 1996). The primary consequences of global warming are rapid changes in surface temperature–about 0.3°C/decade (IPCC, 1992 in Wiel et al., 1996)–and precipitation changes. The consequent expected rise in sea-level (3 to 10 cm/decade) and changes in hydrological and vegetation patterns may have serious effects on society, leading to high risks and substantial costs. Rapid climatic changes are also a threat to current biodiversity and ecosystems (Stanners & Bourdeau, 1995). Acid rain on the other hand, has already caused lakes and possibly forests to decay and has adversely affected aquatic ecosystems and aquifers (Mannion & Bowlby, 1992). Acidification can also contribute to a reduction in the quality of groundwater and damage materials and crops.

Thus, unless there are rapid improvements in the renewable energy technologies sector, it is evident that a reduction in global energy use is of great urgency from an environmental point of view. This also has many economical advantages and some political implications.
The share of the building sector

About one third of the global primary energy is used in the building sector (Levine et al., 1996). The use of energy in buildings accounts for about 25-30% of total energy-related carbon dioxide (CO₂) emissions, making it 19-22% of all anthropogenic CO₂ and 10-12% of the net radiative forcing that is inducing global warming (IEA, 1994 and Levine, 1996 in Wiel et al., 1996). In cold countries, such as Sweden and Canada, buildings use the largest share of national primary energy. In Sweden, more than 40% of all energy is spent on heating, cooling and supplying electricity to buildings (NUTEK, 1995). The figure is around 37% for Canada (Natural Resources Canada, 1996).

A large share of energy use in buildings is tied to fenestration performance. According to Granqvist (1989), 7% of Sweden’s energy is "lost" through windows. Moreover, as levels of insulation through opaque elements tend to increase, so does the tendency to increase glass areas and the use of special glazing (Pfrommer et al., 1995).

Solar-protective glazing

Energy transfer into and out of buildings through transparent components is often many times larger than energy transfer through opaque elements. Thus, while windows can be great energy losers, they can also provide a substantial amount of “free” energy to the building because they are transparent to a large part of the solar spectrum. A surface perpendicular to the sun can receive a substantial amount of energy (up to 1000 W/m² at the Earth surface) some of which can be used in a building as heat or light source (Granqvist, 1989).

In buildings that already benefit from “free” heat from occupants, artificial lighting and equipment such as offices, solar gains can also result in overheating problems that need to be corrected by artificial cooling. In these cases, solar gains need to be controlled in order to avoid excessive cooling or overheating of the building.

A number of products, like heat-absorbing glass and reflective coatings on glass, have entered the market over the last thirty years in response to the increasing cooling and overheating problems in office and commercial buildings. Reflective and tinted glazings can be effective in warm climates but their use is questionable in cold and temperate climates where cooling is often only required during the warm season, especially as improvements in lighting and equipment efficiency are contributing to a gradual reduction in internal heat loads. Solar-protective glazings
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also usually have a lower visual transmittance resulting in lower daylighting availability in the space. They can also induce visually disturbing inter-reflection effects between buildings. From an architectural point of view, reflective and tinted glazings modify the view into and out of the building, therefore affecting the contact with the outside world.

1.3 Background

Previous research indicates that a reduction in solar gains through windows through the use of solar-protective glazing or shading devices can possibly yield no energy savings at all or, worse, can increase a building’s energy use in cold or temperate climates. Treado et al. (1983) showed, for instance, that solar films on window panes provided no energy savings in regions with important heating loads. In their study, films generally contributed to a reduction in cooling loads and to an increase in heating loads due to the reduction of useful solar gains in the winter. Their findings agree with studies of solar-protective devices in cold climates (Bilgen, 1994; Hunn et al., 1990), which showed that shading devices generate increases in heating loads. One study (Hunn et al., 1993) even showed that solar-protective devices like exterior shades can be net energy losers in cold climates. Even in the climate of Florida, it has been shown (Pletzer et al., 1988) that tinted windows (heat-absorbing) yield only 1-3% annual energy cost savings.

1.4 Research problem and objectives

In this research, the annual energy use for heating and cooling an office room equipped with different types of solar-protective glazings is analysed. The solar-optical properties of the glazing, the glazing area and the room’s orientation, as well as the climate, are varied parametrically. Only cold climate cities are included in the study since many studies of solar-protective glazings have already been made for warm climates. Peak loads and indoor temperatures are also briefly analysed although these aspects are not the main focus of the research.

The parametric study is carried out by simulation of the energy use with the program DEROB-LTH, which has recently been supplemented with an improved angular dependent calculation module for windows. The program WINDOW 4.1 is used in conjunction with DEROB-LTH to determine the thermal and optical properties of glazings.
The main objective of this study is to yield a framework of data and knowledge on energy use trends in buildings equipped with solar-protective glazing as a basis for developing design guidelines for consultants and architects. The study also pursues the following objectives:

- Compare the annual energy savings achieved with solar-protective glazing with the annual energy use yielded by standard, clear glazing and low-emissivity coated glazing.
- Estimate the potential for reducing heating and cooling loads in an office room through the use of an energy-efficient glazing strategy.
- Identify which parameters (glazing type or orientation, for example) primarily influence the energy use in the room.
- Provide a set of annual energy use totals with a range of solar-protective glazing for future comparisons with energy savings provided by shades and advanced glazings such as smart windows.
- Identify glazing solutions or strategies which result in a waste of energy compared with standard, clear glazing.
2 Theory

2.1 Some useful definitions

Glazings are usually described and compared by glass manufacturers with reference to a few standard terms such as solar and visual transmittance, shading coefficient or solar heat gain coefficient. These same properties are used throughout this report. Some useful definitions are introduced below.

2.1.1 Reflectance, absorptance and transmittance

Glazing is most often qualified according to its solar-optical properties reflectance, absorptance and transmittance. The reflectance ($\rho_s$) is the fraction of incident flux that is reflected from the glazing, the absorptance ($\alpha_s$) is the fraction of incident flux absorbed by the glazing while the transmittance ($\tau_s$) is the fraction that is transmitted through the glazing. These optical properties are distinguished from the related quantities reflectivity, absorptivity and transmissivity as follows: the “-ivity” ending refers to the inherent properties of a bulk sample of material while the “-ance” ending refers to the property of a sample of specific thickness of a substance or of a combination of substances (ASHRAE, 1997).

The solar transmittance is the glazing transmittance over the whole range of the solar spectrum while the visual transmittance usually refers to the glazing transmittance only for the visual range of the solar spectrum i.e. for $0.4 < \lambda < 0.76 \mu m$ ($\lambda =$ wavelength). Manufacturers usually give the visual transmittance because it determines how well one can see through the glazing and how much natural light can be used in the building to illuminate tasks.
2.1.2 Solar heat gain coefficient

The Solar Heat Gain Coefficient (\(SHGC\)) is the fraction of incident irradiance (solar radiation incident on the glazing) that enters the building and becomes heat in the space. It includes both the directly transmitted portion and the absorbed and re-emitted portion of solar radiation. It is defined by ASHRAE (1997) in the following way:

\[
SHGC = \frac{q_i}{E_i} \quad (\text{-}) \quad (2.1)
\]

and,

\[
q_i = E_i (\tau_s + N_I \alpha_s) \quad (W/m^2) \quad (2.2)
\]

thus,

\[
SHGC = \tau_s + N_I \alpha_s \quad (\text{-}) \quad (2.3)
\]

where

- \(q_i\) is the total solar gain (heat flow per unit area) (W/m\(^2\)),
- \(E_i\) is the solar irradiance (W/m\(^2\)),
- \(\tau_s\) is the glazing solar transmittance (\%),
- \(N_I\) is the inward flowing fraction of the absorbed energy (\%),
- \(\alpha_s\) is the glazing solar absorptance (\%)

2.1.3 Shading coefficient

The shading coefficient is defined as the ratio of the \(SHGC\) of a glazing system for a particular angle of incidence and incident solar spectrum to that of clear, single pane glass (also called the “standard reference glazing” in which \(\tau_s = 0.86, \rho_s = 0.08, \text{ and } \alpha_s = 0.06\) at normal incidence) with the same angle of incidence and spectral distribution, or, as described in ASHRAE (1997):

\[
SC = \frac{SHGC(\theta)_{\text{test}}}{SHGC(\theta)_{\text{ref}}} \quad (\text{-}) \quad (2.4)
\]

A good solar-protective glass or a good shade thus has a low \(SC\) while a poor solar-protective glass or a poor shade has a high \(SC\). Note that in some countries the reference glazing consists of a double pane clear glass assembly.
2.2 Energy transfer through windows

Heat transfer through windows comprises additive contributions from thermal radiation, conduction in solids and gases and gas convection (Granqvist, 1989). This is illustrated in Figure 2.1.

![Figure 2.1](image)

**Figure 2.1  Heat transfer through windows**

2.2.1 Conduction and convection

Conduction and convection processes can be reduced by multiple pane assemblies or by interposing materials between panes, for instance by replacing the air by an inert noble gas. Argon is the most common choice for a substitute gas fill but further reductions in window U-value can be achieved with krypton and xenon. There are also a number of alternative materials and glazings such as aerogels, transparent insulation, evacuated glazing, which have the potential to further reduce heat losses by conduction-convection processes.

2.2.2 Radiation

Radiation from the sun is typically confined to the $0.25 < \lambda < 3 \ \mu m$ wavelength range. The visible world is a reflection of the energy in the $0.4 < \lambda < 0.76 \ \mu m$ range as illustrated in Figure 2.2.
When direct and diffuse solar radiation reaches a window pane, part of the energy is reflected by the glass surface, part is transmitted and part is absorbed in the glass (Fig. 2.1). For each wavelength, the sum of the fractions of the total energy reflected, transmitted and absorbed through the glass is equal to one (or 100%). This is one of the fundamental laws of energy conservation:

\[
\alpha(\lambda) + \rho(\lambda) + \tau(\lambda) = 100\%
\]  

(2.5)

where

- \( \alpha(\lambda) \) means absorptance as a function of wavelength \( \lambda \)
- \( \rho(\lambda) \) means reflectance as a function of wavelength \( \lambda \)
- \( \tau(\lambda) \) means transmittance as a function of wavelength \( \lambda \)

One of the fundamental properties of matter is that it emits energy in the form of electromagnetic waves. For non-ideal or non-black bodies, the emitted energy or radiation is a function of the fourth power of the temperature of this material multiplied by a constant and the material’s emittance. This can be written as:

\[
q_{\text{rad}} = \varepsilon \sigma (T + 273.15)^4
\]

(W/m\(^2\))  

(2.6)
where

\[ q_{rad} \text{ is the total emitted radiation (W/m}^2) \]
\[ \varepsilon \text{ is the emittance of the material (-)} \]
\[ \sigma \text{ is Stefan-Boltzmann's constant (W/K}^4\text{m}^2) \]
\[ T \text{ is the temperature of the body (K).} \]

The emittance is a property of the surface material. For objects at room temperature, the emitted radiation is highest at wavelengths around 10 µm. Thus, most of the radiation emitted by people and interior building surfaces is in the form of long-wave radiation.

Clear glass transmits most of the solar radiation, or short wavelength energy falling on it. This property allows us to see through the glass and to use light from the sun to illuminate tasks. However, clear glass is opaque to most of the infrared radiation (especially longer wave radiation). Since objects at room temperature emit radiation mostly in the form of long wave radiation with a peak at 10 µm, most of the energy absorbed by inner surfaces of buildings and by people and reradiated in the infrared spectrum is “trapped” by the glazing which is essentially opaque to these wavelengths.

Thermal radiation exchanges can be modified by coatings, surface treatments of glass or colouring that can reduce the amount of solar radiation transmitted to the interior of a building. These special glazings and coatings are described in the following section.

### 2.3 Glazing types

The glazings included in this study belong to the following main categories:

1. Clear glass
2. Solar-protective glass (reflective and heat-absorbing)
3. Low-emissivity coated glass

This section gives an overview of these glazing types and also presents some commercially available technologies that will permit a dynamic control of solar gains throughout the year.

Solar-protective glass is used in warm climates to avoid overheating due to solar radiation. The most common types of solar-protective glazings are reflective and heat-absorbing (or tinted) glass. The goal is to block radiation in the infrared range as much as possible while reducing radia-
tion in the visual range as little as possible. According to Granqvist (1989), it is possible to exclude most of the infrared radiation (about 1/2 of the total solar spectrum) with no effect on radiation in the visual range.

2.3.1 Coated glass

2.3.1.1 Reflective glass
Reflective glass is one type of solar-protective glass. It is usually coated with thin layers of metals like copper, silver, gold, etc., or with thin layers of semiconductors that “boost” the reflectance of the glazing to solar radiation at the expense of the transmittance, especially at infrared wavelengths ($0.7<\lambda<3\ \mu m$), in order to reduce the solar heat gain. Metal layers are generally used in enclosures in hermetically sealed multiple glazing units while semiconductor layers can be applied to external surfaces (Granqvist, 1989). Reflective glass has been popular in commercial buildings but has not found much acceptance in residential buildings.

2.3.1.2 Low-emissivity coated glass
Along with multiple pane systems, low-emissivity coatings are especially used in cold climates to reduce heat losses through windows. These glazings are therefore not part of the solar-protective glazing family. Low-emissivity coatings have, as the name implies, a lower emittance (typically around 0.1-0.2) which reduces thermal radiation losses to the outside. Such coatings, which may combine a high solar and visible transmittance, are manufactured by all major glass and glazing companies throughout the world. They represent a mature technology, are widely applied and are being increasingly used in double and triple glazed units to achieve very high thermal resistance whilst preserving good levels of solar and light transmittance (Hutchins et al., 1996). According to Granqvist (1989), low-e coatings can improve the thermal insulation of a double glazed window by a factor of 2 without reducing the solar transmittance.

2.3.2 Homogeneous glass

2.3.2.1 Clear glass
Clear glass is probably the most common type of glazing, especially in housing. It is not a solar-protective glazing but is often used in combination with solar-protective glass in multiple pane assemblies.
2.3.2.2 Heat-absorbing or tinted glass

Heat-absorbing or tinted glass is made by the float process in the same way as clear glass. Tinted glass is generally used to avoid excessive solar heat gain and is thus one of the main types of solar-protective glazing. In tinted glazing, the solar absorptance of the glass is increased and the reflectance is retained thus lowering the transmittance. The absorbed energy leads to a heating of the glass (hence the name “heat-absorbing”) and a concomitant reemission of thermal energy so that total energy transmission is lowered. Tinted glazing absorbs solar heat and re-emits this heat back to both sides of the glazing (inside and outside). This secondary heat transmission towards the inside of the building by way of re-radiation and convection from the inner surface of the glazing is one of the main drawbacks of this glazing type for solar protection applications. However, in double-pane windows the tinted glazing is placed on the outside to reduce these energy transfers to the building interior (Pletzer et al., 1988).

2.3.3 Advanced glazing technologies

Some more advanced glazing technologies that are mainly at a research stage are worth mentioning since they represent very promising technologies for a dynamic control of solar radiation in the future. They are especially interesting for temperate climates where the glazing must have dual qualities i.e. limit heat losses during the winter and prevent overheating during the summer. Switchable or “smart” windows such as photochromic, electrochromic or thermochromic glass change their optical properties as a function of incident solar radiation, an applied voltage or temperature.

The photochromic principle has been widely applied to sunglasses. Ultraviolet radiation causes a reversible formation of anisotropic silver specks, which are strongly absorbent particularly at short wavelengths. The optical properties of this glazing are thus governed by a darkened and cleared transmittance (typically ranges from 5-90%) (Granqvist, 1989).

Electrochromism is a reversible colour change in a material by injection of ions under an applied electric current (Lampert, 1984 in Orioli et al., 1990). Electrochromism is possible with layers of oxides of transition metals (such as tungsten, vanadium, nickel, etc.) whose optical properties are altered by varying their content of small mobile ions (H+, Li+, etc.). Additional layers serving as transport ion storage, ion conductor and electric conductor are also required (Granqvist, 1989). Research and development of transparent electrochromic materials and devices for smart
window applications have burgeoned both in academia and industry since the mid-1980s. Electrochromic glazings are available commercially but research is still necessary in order to guarantee the long term stability of the switching and to scale up the surfaces to large window areas (Orioli et al., 1990).

Thermochromic glazing has optical properties that depend reversibly on the temperature i.e. the transmittance goes down once a certain temperature is exceeded. This phenomenon, which is well known for inorganic materials in the liquid and solid state (Sone et al., 1987 in Granqvist, 1989) as well as in many organic materials, is of interest for automatic irradiation control.
3 Method

The research problem is approached through a parametric study i.e. a study where only one independent variable (for example the glazing type, area, orientation or climate) is varied at a time. The impact of the change in each independent variable on dependent variables (for example energy use, peak loads and indoor temperature) is analysed. As in any study, a number of constant parameters or control variables are involved. These parameters, as well as the independent and dependent variables, are described in the following sections.

3.1 Constant parameters

3.1.1 Office room

3.1.1.1 Geometry

The room was a standard 2.9 m wide, 4.2 m deep and 2.7 m high (interior dimensions), single-occupant office. Although the glazing-to-wall area ratio (GWAR) was varied during the study, the glazing was located 1.0 m from the floor for all cases. A 0.1-m wide wood frame was assumed around the glazing, which was built as one single surface in DEROB-LTH to simplify the model (Fig. 3.1).

1. Except for 70% GWAR since the glazing covered most of the wall area in that case.
3.1.1.2 Construction

In the model, thermal exchanges were selectively constrained in order to isolate the energy effects of interest i.e. the impact of glazing solar-optical properties on energy use. The room was assumed to be surrounded by contiguous office space at the same temperature. Thus, “interior” partitions, the floor and the ceiling were modelled as adiabatic surfaces (having no heat transfer) and wrapped in a thick insulation layer (20 m). Thermal exchanges through the partition facing the “exterior” were controlled by adjusting the insulation thickness in the opaque wall as a function of thermal losses through the window. This method, which has been used by other authors such as Sullivan et al. (1987), permitted the inclusion of windows with a range of U-values in the study. Details of this procedure can be found in Appendix A. A description of the construction of the room with material properties entered in DEROB-LTH is presented in Table 3.1 below.
Table 3.1 Construction of the office room.

<table>
<thead>
<tr>
<th>Partition</th>
<th>Material (Exterior ⇒ interior)</th>
<th>Thickness (mm)</th>
<th>Conductivity (κ) (W/m°C)</th>
<th>Specific heat (Wh/kg°C)</th>
<th>Density (kg/m³)</th>
</tr>
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<tbody>
<tr>
<td>Interior walls</td>
<td>Super-insulation</td>
<td>20 000</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Air space (21°C)</td>
<td>20</td>
<td>0</td>
<td>0.28</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>2 gypsum boards</td>
<td>26</td>
<td>0.22</td>
<td>0.23</td>
<td>900</td>
</tr>
<tr>
<td>Floor and ceiling</td>
<td>Super-insulation</td>
<td>20 000</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Concrete</td>
<td>100</td>
<td>1.70</td>
<td>0.24</td>
<td>2300</td>
</tr>
<tr>
<td>Exterior wall</td>
<td>Ext. mat. + air space</td>
<td>8</td>
<td>0.04</td>
<td>0.24</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>Insulation board</td>
<td>variable</td>
<td>0.053</td>
<td>0.18</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Min. wool (74%) + wood studs (26%)</td>
<td>variable</td>
<td>0.056</td>
<td>0.28</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>2 gypsum boards</td>
<td>26</td>
<td>0.22</td>
<td>0.23</td>
<td>900</td>
</tr>
<tr>
<td>Frame</td>
<td>Wood</td>
<td>100</td>
<td>0.34</td>
<td>0.76</td>
<td>550</td>
</tr>
<tr>
<td>Door</td>
<td>Super-insulation</td>
<td>20 000</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Air space (21°C)</td>
<td>20</td>
<td>0</td>
<td>0.28</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Wood (Masonite)</td>
<td>6</td>
<td>0.13</td>
<td>0.37</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>Non vent. air space</td>
<td>28</td>
<td>0.18</td>
<td>0.28</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Wood (Masonite)</td>
<td>6</td>
<td>0.13</td>
<td>0.37</td>
<td>1000</td>
</tr>
</tbody>
</table>

3.1.1.3 Surface properties

Interior finishes in the model were light grey paint for the interior walls, the door, and the frame, white paint for the ceiling, and a dark carpet for the floor. Emittance and absorptance values for the interior surfaces entered in the model were as described in Table 3.2.

Table 3.2 Properties of interior surfaces.

<table>
<thead>
<tr>
<th>Partition</th>
<th>Surface type</th>
<th>Emittance (%)</th>
<th>Absorptance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interior wall</td>
<td>Light grey paint</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>Frame (interior)</td>
<td>White paint</td>
<td>90</td>
<td>20</td>
</tr>
<tr>
<td>Door</td>
<td>Dark carpet</td>
<td>90</td>
<td>70</td>
</tr>
</tbody>
</table>

The exterior surfaces of the exterior wall and frame were assigned an absorptance of 0% to limit solar radiation effects through the opaque wall parts. During preliminary tests, it appeared that for cases with no windows and a small insulation thickness in the opaque wall, heating and cooling loads varied slightly when the orientation of the room was
changed. South facing rooms had a lower heating and higher cooling load than north facing rooms. Thus, there was some effect of solar radiation incident on the opaque wall due, mainly, to the wall absorptance, which was set fairly high at the beginning (55%). The goal of this study is to assess the impact of glazing solar-optical properties on energy use. If the solar radiation incident on the wall influences heating and cooling loads, it becomes difficult to decide whether energy loads are influenced by solar radiation incident on the window or the wall. This problem is avoided by setting the wall surface absorptance to 0%.

The exterior surface emittance was also set to 0%. After a series of tests with a windowless room, it was observed that heating and cooling loads obtained with 0% absorptance and 0% emittance were closer to the loads obtained with surface properties of an ordinary yellow brick wall (absorptance = 55%, emittance = 90%) (see Appendix B). By changing the surface emittance, the radiative component in the surface resistance was slightly changed, thus influencing the wall U-value. However, a rapid estimate showed that the impact of this change on the wall U-value was less than 6% for the worst case (largest wall area and smallest insulation thickness).

3.1.2 Internal loads

In this study, the internal loads consisted of the heat from one occupant (90 W), one computer and monitor (120 W) and energy-efficient lighting (120 W).

For the occupant, ASHRAE (1997) suggests that about 115 W/person should be assumed for sedentary work in an office. Adamson et al. (1986) propose 80-100 W/person. Olgyay (1963) suggests around 117 W/person for sedentary work. In this study, 90 W was chosen for the occupant as it was assumed that the person is not in his/her office all the time. This value corresponds to around 80% of the value given by ASHRAE (1997) and Olgyay (1963) and falls within the range given by Adamson et al. (1986).

According to ASHRAE (1997), personal computers and monitors with 125-133 W of total measured power consumption produce 29.7-35.7 W of radiant heat and 89.3-103.3 W of convective heat. Thus, the total heat produced corresponds, approximately, to the total measured electrical power consumption. For this study, the power consumption of two computer and monitor sets was measured². The total power consumption was around 120 W when the equipment was switched on and 6 W for one of the computers (the Pentium) when switched off. We assumed that
most of this power was radiated and convected as heat in the room and, thus, a heat gain of 120 W was entered in the model for the computer and monitor together. The switch-off mode heat gain was neglected.

ASHRAE (1996) suggests the use of 20-50 W/m² for lighting and normal equipment electrical load in an office. In this study, a relatively energy-efficient office lighting was assumed with total loads from lights and equipment of about 20 W/m². Heat gains from lights vary greatly depending on which type of lighting is used, the energy efficiency and efficacy of the lights, etc. Thus, authors use a range of different values for heat gains from lights. Some are presented in Appendix C. In this study, a rather energy-efficient lighting system consisting of low energy fluorescent lamps producing around 10 W/m² was assumed. This value is realistic for contemporary Sweden, according to Svendenius (pers. comm., 1996) and was measured by NUTEK (1994). Laine & Saari (1994) estimated the same value in an experimental low-energy office in Finland. The present study is aimed at non-daylit office rooms i.e. daylighting was not used to replace and dim artificial lights. This will be the subject of future studies by the author.

The internal loads were assumed during normal working hours (08.00-17.00), Monday to Friday. At lunchtime (12.00-13.00), the load from the occupant was removed but the computer, monitor and lighting remained switched on. The total internal heat gains were thus as described in Table 3.3.

Table 3.3  Total internal heat gains during weekdays.

<table>
<thead>
<tr>
<th>Time (hour)</th>
<th>Total internal heat gain (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00.00-08.00</td>
<td>0</td>
</tr>
<tr>
<td>08.00-12.00</td>
<td>330</td>
</tr>
<tr>
<td>12.00-13.00</td>
<td>240</td>
</tr>
<tr>
<td>13.00-17.00</td>
<td>330</td>
</tr>
<tr>
<td>17.00-00.00</td>
<td>0</td>
</tr>
</tbody>
</table>

2. One computer was a Pentium-133 MHz with 43 cm colour screen (with a screen saver). The other computer was a 486 Dx IBM-66MHz with a 38 cm colour screen (no screen saver).

3. The total internal heat gains monitored in this project were 300-400 W/office, as is the case in the present study.

4. A non-daylit building is one in which no control system is used to alter electric light level based on the interior daylit illuminance, according to the definition for daylit buildings by Johnson & Besant (1993).
3.1.3 Ventilation

Ventilation rates required for single office rooms vary greatly according to country and building regulations. The Swedish building code BBR 94 (Boverket, 1997) recommends a continual air change of not less than 0.35 L/s·m² of floor area (4.3 L/s for the office room studied). Engberg (1993) suggests a rate of 10 L/s for offices. The same ventilation rate was measured in a number of typical office buildings in the United Kingdom (Leighton & Pinney, 1990) although an English norm (CIBSE-Guide A rev. section 2, 1993 in Olesen, 1997) recommends 8 L/s-person. A German norm (DIN 1946 part 2, 1994 in Olesen, 1997) recommends 11 L/s-person. A Nordic guideline NKB-61 (NKB, 1991 in Olesen, 1997) recommends 3.5 L/s-person plus 0.7 L/s·m² (12 L/s for the office room studied). A European standards organisation (CEN) recommends 4-10 L/s-person plus 0.4-1.0 L/s·m² for the building (CEN prENV 1752, 1996 in Olesen, 1997). For the office room considered in this study, this corresponds to a rate of 8.9-22.2 L/s. In America, ASHRAE Standard 62-1989R (ASHRAE, 1996 in Olesen, 1997) sets the standard minimum ventilation rate at 7.5 L/s-person for office spaces but recommends 3.0 L/s-person plus 0.35 L/s·m² or 0.66 L/s·m². For the office room used in this study, the ventilation rate should thus be 8 L/s. Note that the previous ASHRAE standard (ASHRAE 62-1989) recommended 10 L/s-person (ASHRAE, 1989).

In this study, a constant ventilation rate of 10 L/s (1.1 ach) was used. This value seems to represent an average of the recommended ventilation rates for single offices according to different international standards. No recovery of exhaust air was assumed in order to simplify the model.

3.1.4 Infiltration

The infiltration rate assumed in this study was 0.1 ach. The Swedish building code recommends a maximum air leakage of 1.6 L/s·m² at a pressure difference of ±50 Pa for non-residential premises (Boverket, 1997). This is about 1.4 ach for the office room used in this study. Also, measurements in 6 Canadian office buildings and 8 U.S. office buildings revealed air leakage between 610-5220 cm³/s·m² at 75 Pa pressure difference (corresponding to 0.5-4.5 ach for the office room studied) (Tamura & Shaw, 1976; Persily & Grot, 1986 in ASHRAE, 1997). The National Association of Architectural Metal Manufacturers specifies a maximum leakage per unit of exterior wall area of 300 cm³/s·m² at a pressure difference of 75 Pa exclusive of leakage through openable windows (ASHRAE, 1997). This corresponds to 0.25 ach for the office room studied here. Blomsterberg (1990) measured infiltration rates between 0.2-0.7 ach at 4
Pa pressure difference in low-rise residential buildings. Finally, Hutcheon & Handegord (1983) report that measured infiltration rates were between 0.11-0.34 ach for tight houses and between 0.37-0.6 ach for electrically heated houses of varied constructions.

Although most numbers reported here are higher than the infiltration rate used in this study, it should be noted that:

1. the Swedish standard is an upper limit,
2. the measurements reported by ASHRAE are performed under pressure conditions higher than the ones prevailing during ordinary running conditions,
3. buildings monitored by Tamura & Shaw (1976), Persily & Grot (1986) and Hutcheon & Handegord (1983) were rather old; new buildings can be expected to be more airtight and
4. measurements by Blomsterberg (1990) were only for houses; office buildings with non-openable windows should be more airtight than houses.

Thus it can be speculated that an infiltration rate of 0.1 ach is quite realistic for a modern office building.

3.1.5 Indoor temperature set points

The recommended indoor air temperature depends on the country where the building is erected, the building function, standard professional practice, energy cost, etc. The choice of indoor temperature set points for heating and cooling can be based on the comfort zone for the country or region considered. The comfort is, according to Olgyay (1963), the situation where no feeling of discomfort occurs. Table A.6 in Appendix D presents some comfort zone limits according to different authors. This table shows, for example, that the English comfort lies roughly between 14-23°C, while the American comfort is somewhere between 18-29°C. Olgyay (1963) states that the comfort zone lies between 18.9-24.4°C in the winter and 20.0-27.8°C in the summer for the Temperate Zone of the United States. According to this author, the ideal temperature would aim towards the middle of these limits. In Sweden, where the houses are typically well insulated and have a heating system, the comfort zone can be expected to be close to the American one in the Temperate Zone of the United States. In fact, according to General Recommendations from the Swedish Board of Health and Welfare (Allmänna råd från socialstyrelsen, 1988), the air temperature should not drop below 18°C at any time in all building types and should never rise above 28°C. These limits are similar to the American comfort limits suggested by Olgyay (1963).
In this study, the indoor temperature was thus set to 20°C for heating during working hours (08.00-17.00 hours) and to 18°C the rest of the time (17.00-08.00 hours). For cooling, the temperature set points were 24°C during working hours and 28°C outside working hours. These indoor temperatures fall within the range prescribed by the General Recommendations from the Swedish Board of Health and Welfare and the comfort zone suggested by Olgyay (1963). Unfortunately, the version of the energy simulation program used (DEROB-LTH-97.02) does not allow the modelling of different temperatures during weekends so the same temperature set points were used for every day of the week.

3.1.6 Other parameters

The ground reflectance was set to 30% in the model since most cities included in the study have higher ground reflectance than normal due to snow drifting.

The exterior film coefficients were split into a constant, convective part to the outdoor air and a radiative part calculated by the simulation program (T⁴ dependent on the ground and sky temperatures) (Kvist, 1997). The exterior convective film coefficient was set at 11 W/m²°C and the interior convective film coefficient was calculated by the program based on indoor temperature.

3.2 Independent variables

3.2.1 Glazing type

Glazing assemblies were selected to cover a wide range of shading coefficients (0.16-0.86) and to represent the main solar-protective glazing types (reflective and absorbing) as well as low-emissivity and clear glass in double and triple-pane assemblies. The glazing assemblies were chosen from Pilkington glass manufacturer product list (Pilkington, 1989, 1990 and 1995). The glass thickness was 6 mm and the space between glazing layers was 12 mm for all cases. The glazing assemblies included in the study are presented in Table 3.4 below with their thermal and optical properties. The solar-optical properties of each individual glass layer are presented in Table 3.5. The properties presented in Tables 3.4 and 3.5 were calculated with the program WINDOW 4.16 (LBL, 1994) for typical Swedish environmental conditions.
Table 3.4 Glazing assemblies and their thermal and optical properties.

<table>
<thead>
<tr>
<th>#</th>
<th>Glazing</th>
<th>Layers</th>
<th>U-value (W/m²°C)</th>
<th>SHGC</th>
<th>SC</th>
<th>τ⊥ (%)</th>
<th>τ⊥ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>D-reflective bronze</td>
<td>bronze reflective argon clear</td>
<td>2.06</td>
<td>0.14</td>
<td>0.16</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>B</td>
<td>D-reflective blue</td>
<td>blue reflective air clear</td>
<td>2.62</td>
<td>0.27</td>
<td>0.32</td>
<td>18</td>
<td>27</td>
</tr>
<tr>
<td>C</td>
<td>T-reflective silver</td>
<td>silver reflective air clear</td>
<td>1.87</td>
<td>0.38</td>
<td>0.44</td>
<td>30</td>
<td>29</td>
</tr>
<tr>
<td>D</td>
<td>T-absorbing blue</td>
<td>blue absorbing air clear</td>
<td>1.87</td>
<td>0.41</td>
<td>0.48</td>
<td>31</td>
<td>44</td>
</tr>
<tr>
<td>E</td>
<td>D-absorbing blue</td>
<td>blue absorbing argon clear</td>
<td>2.63</td>
<td>0.48</td>
<td>0.56</td>
<td>38</td>
<td>48</td>
</tr>
<tr>
<td>F</td>
<td>T-low-emissivity</td>
<td>low-e coated argon clear</td>
<td>1.00</td>
<td>0.58</td>
<td>0.68</td>
<td>44</td>
<td>65</td>
</tr>
<tr>
<td>G</td>
<td>T-clear</td>
<td>clear</td>
<td>1.88</td>
<td>0.65</td>
<td>0.76</td>
<td>55</td>
<td>73</td>
</tr>
<tr>
<td>H</td>
<td>D-clear</td>
<td>clear argon clear</td>
<td>2.65</td>
<td>0.74</td>
<td>0.86</td>
<td>67</td>
<td>80</td>
</tr>
</tbody>
</table>

D = double pane; T = triple pane

5. The properties are given for the glazing only, not the whole window with frame.
6. The glazing manufacturer’s measured optical properties at normal incidence for individual glazing layers were used in the WINDOW-4.1 calculations.
7. Environmental conditions were the same as NRFC/ASHRAE standard environmental conditions except that outdoor/indoor temperatures were 0°C / +20°C. The wind speed was 5 m/s and sky temperature was 0°C.
Table 3.5 Glass layers and their solar-optical properties.

<table>
<thead>
<tr>
<th>Glass</th>
<th>$\tau_{\perp}$ (%)</th>
<th>$\rho_{\perp \text{front}}$ (%)</th>
<th>$\rho_{\perp \text{back}}$ (%)</th>
<th>$\alpha_{\perp}$ (%)</th>
<th>$\varepsilon_{\text{front}}$ (%)</th>
<th>$\varepsilon_{\text{back}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>bronze reflective</td>
<td>6</td>
<td>21</td>
<td>37</td>
<td>73</td>
<td>85</td>
<td>41</td>
</tr>
<tr>
<td>blue reflective</td>
<td>21</td>
<td>18</td>
<td>32</td>
<td>61</td>
<td>85</td>
<td>66</td>
</tr>
<tr>
<td>silver reflective</td>
<td>43</td>
<td>28</td>
<td>35</td>
<td>29</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>blue absorbing</td>
<td>46</td>
<td>5</td>
<td>5</td>
<td>49</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>low-e coated</td>
<td>73</td>
<td>9</td>
<td>10</td>
<td>18</td>
<td>85</td>
<td>15</td>
</tr>
<tr>
<td>clear</td>
<td>82</td>
<td>7</td>
<td>7</td>
<td>11</td>
<td>85</td>
<td>85</td>
</tr>
</tbody>
</table>

Note that the bronze and blue reflective glasses have a higher absorptance ($\alpha_{\perp}$) than the blue absorbing glass due to a low solar transmittance. The effect of this on the 2 reflective glazing assemblies is, however, limited due to the clear glass used in the multiple pane assembly as shown by the respective $\text{SHGC}$ which is lower than for the heat-absorbing glazing.

3.2.2 Orientation

The orientation was initially varied by 45° increments. Figure 3.2 represents the orientations studied.

![Figure 3.2 Orientations.](image-url)
3.2.3 Glazing-to-wall area ratio (GWAR)

The glazing-to-wall area ratio (GWAR) was varied in order to represent extreme situations i.e. very small and very large window areas. Thus, 0-, 10-, 20-, 30-, 50- and 70% GWAR were modelled. Although the glazing area was modelled as one single surface in DEROB-LTH, an attempt was made to pick frame areas (0.1 m wide) corresponding to realistic window dimensions as the ones showed in Figure 3.3 below.

![Figure 3.3](image)

“Real” window sizes on which the dimensions in the virtual model were based.

3.2.4 Climate

The study is primarily aimed at cold climates. Thus, climatic data from cities in Scandinavia and Canada was used. Large cities were preferred to small ones since there are generally more office buildings in larger urban agglomerations. Lund (Sweden), Stockholm (Sweden), Luleå (Sweden), Oslo (Norway) and Montreal (Canada) were thus chosen (Table 3.6). Lund was picked because of its proximity to two large cities (Malmö and Copenhagen) and because the climate file for this small city was readily available. Luleå was chosen as an example of extreme northern latitude. Some climatic characteristics for the cities chosen are described in the Table 3.6 below. Average temperatures for each month are also shown in Figure 3.4.
Table 3.6 Climatic characteristics of Lund, Stockholm, Luleå, Oslo and Montreal.

<table>
<thead>
<tr>
<th>City</th>
<th>Year</th>
<th>Geographic location</th>
<th>Outdoor temp. (°C)</th>
<th>Solar radiation (kWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lund</td>
<td>1988</td>
<td>55.72°N13.22°E</td>
<td>-9.1   8.2   27.0</td>
<td>955.9     518.5     872.8</td>
</tr>
<tr>
<td>Stockholm</td>
<td>1988</td>
<td>59.35°N18.07°E</td>
<td>-14.4  6.5   28.2</td>
<td>928.5     458.5     1012.1</td>
</tr>
<tr>
<td>Luleå</td>
<td>1988</td>
<td>65.55°N22.13°E</td>
<td>-27.4  2.6  30.7</td>
<td>882.1     425.6     1049.2</td>
</tr>
<tr>
<td>Oslo</td>
<td>1970</td>
<td>59.55°N10.44°E</td>
<td>-24.7  6.2  32.6</td>
<td>968.7     468.7     1060.0</td>
</tr>
<tr>
<td>Montreal</td>
<td>1994</td>
<td>45.30°N73.37°W</td>
<td>-31.2  6.2  33.5</td>
<td>1279.5   347.9   1870.2</td>
</tr>
</tbody>
</table>

Figure 3.4 Average monthly temperatures in Lund, Stockholm, Luleå, Oslo and Montreal.

Table 3.6 shows that, although all Scandinavian cities included in this study are north of Montreal, Montreal has a colder annual minimum temperature. In fact, average temperatures in the winter (December to February) are the coldest in Montreal as shown in Fig. 3.4. From March to October, the temperature profiles are similar for the 5 cities but Mont-

---

8. This climate file was, in fact, constituted from different years i.e. 1968, 1971-74 and 1976-78.
treal has the highest outdoor temperature in the summer (June to August) and in the autumn. Table 3.6 also shows that there is more solar radiation (global) in Montreal than in the Scandinavian cities. There is also significantly more direct solar radiation in the Canadian metropolis. Note that Oslo and Stockholm have very similar temperature profiles except that Oslo is slightly colder in January and February. The two cities also have similar global, diffuse and direct solar radiation for the whole year.

3.3 Dependent variables

This study focuses on energy use in office rooms equipped with different types of solar-protective glazing. Thus, the main parameter that is observed, analysed and compared as a function of varying glazing strategy and orientation is energy use for cooling and heating the room. Energy use for lighting and equipment is not taken into consideration since it is assumed constant throughout the study. The indoor temperature is also analysed for some cases to identify critically high or low indoor dry-bulb temperatures.

The glazing strategy also influences thermal and visual comfort, availability of daylighting and the view to the exterior of the building. These aspects are not considered in this study. They will be the subjects of future studies by the author.

3.3.1 Energy use

3.3.1.1 Monthly and annual loads

Annual energy use is the main parameter analysed in this study. A number of studies (see, for example, Harkness, 1988; Halmos, 1974) considered the heating or the cooling season only. In cold and temperate climates, energy use must be analysed for the whole year. The temperature and solar radiation fluctuations that prevail in cold and temperate climates demand glazing strategies that perform well during both the cooling and the heating season. Low-solar transmittance glazing systems are often good performers during the cooling season but may result in high heating loads.

The program used for the energy simulations (DEROB-LTH) calculates the space load for cooling and heating. The space load is defined by ASHRAE (1997) as the amount of energy that must be added to or extracted from a space in the form of heat or cooling to maintain thermal
comfort. This amount of energy is generally a function of the outdoor temperature, solar radiation, internal gains, thermal inertia and the effect of wind on both building envelope heat transfer and air leakage. Note that \textit{DEROB-LTH} does not calculate the energy as a function of a thermal comfort temperature but, rather, as a function of set indoor temperature points.

Net building energy use depends on both the space load and the performance of energy systems (primary and secondary equipment) used in the building. There are a large number of heating and cooling systems. For commercial applications, Howell et al. (1998) describe the following systems: all-air and air-water systems, unitary or room conditioners, panel heating and cooling, heat pumps, total energy systems (cogeneration) and heat recovery systems. Each of these systems has variants (for example: simple duct, dual-stream, etc.) and some systems may consist of a combination of the above systems used in different parts of the building or for achieving different functions (heating, cooling, ventilation, humidification). For example, a variable air volume system might be used in central zones while radiant ceiling panels are installed in the perimeter zones for heating. The problem is even more complicated if different energy sources are used to provide different services, e.g. if oil or gas is used for the heating system and electricity for ventilation or cooling.

The performance of the heating or cooling system is often referred to as the \textit{COP} (coefficient of performance) which is defined as the benefit of the cycle (amount of heat removed or supplied) divided by the energy required to operate the cycle (ASHRAE, 1997) or

\[
\text{\textit{COP}} = \frac{\text{useful heating or refrigerating effect}}{\text{net energy supplied from external source}}
\]

Although all-air systems are common in offices, it appears difficult to define a general \textit{COP} for heating and cooling since there are so many variants to each system and since the \textit{COP} also depends on a number of other factors such as, for example, the capacity of the equipment used, the building design, the operation, the temperatures to which the system operates, etc. In this study, it was assumed that the \textit{COP} for heating and cooling were equal. In other words, the same amount of energy was used to produce 1 kWh of heat or 1 kWh of cooling. Thus, totals of energy use presented in this report assume heating and cooling loads in a 1:1 ratio. This is rarely the case in a real building and the results should be interpreted with this assumption in mind. The choice of an optimal glazing option may be highly dependent on the respective \textit{COPs} for the cooling and heating systems. For cases where the heating system has a much higher
COP than the cooling system, glazing options resulting in a low cooling load may be more energy-efficient annually. Note, however, that there are advantages in considering only space loads: the figures obtained are more general and can be adapted to represent any building. Moreover, the figures presented in this report do not depend on the performance of specific energy systems, which are likely to improve in the future.

3.3.1.2 Peak loads
Peak loads often determine the size of the cooling and heating equipment, which has a significant impact on building costs. Glazing is often selected to limit the size of the cooling or heating equipment required in a building. In this study, peak loads were analysed briefly for 2 cities (Lund, Montreal) and 8 glazing types with 30% GWAR. Only the south orientation was studied. Peak hours were identified for each city as well as climatic and design conditions associated with the peak loads for heating and cooling. Design peaks were then compared for different glazing options in each climate.

3.3.2 Indoor temperature
Solar-protective glass is often used in buildings to improve thermal comfort, especially during the summer. Thermal comfort depends on a number of factors such as the radiant temperatures (temperature of the surrounding surfaces), solar radiation, clothing, physical activity, local air velocity, draught and humidity (Wall, 1996). A complete analysis of thermal comfort is thus a complex task that is well outside the scope of the present study. However, indoor temperature (dry-bulb) was analysed as the energy simulation program used calculates this value for one point located at the centre of the room. The same air temperature is assumed in the whole room. The indoor temperature is not a measure of thermal comfort but can indicate extreme indoor environmental conditions. Note that DEROB-LTH also gives the operative temperature at the centre of the room. This value is a simple average between the room surfaces and air temperature. As comfort in an office may be highly dependent on the temperature near the window due to ordinary office layouts, the operative temperature given by DEROB-LTH was judged inappropriate for assessing the thermal comfort in this case.

The indoor temperature was analysed for 8 different glazing options with 30% GWAR orientated south in two climates (Lund, Montreal). For this analysis, no cooling was used in the simulations and temperatures thus fluctuated naturally (above the heating temperature set point)
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as a function of climatic conditions and glazing type. The number of hours with temperatures outside the comfort zone were computed for each alternative and compared.

3.4 Simulation programs

3.4.1 DEROB-LTH (version 97.02)

The building energy performance was simulated with the program DEROB-LTH-97.02. DEROB is an acronym for “Dynamic Energy Response of Buildings”. This program was originally developed at the University of Texas (Arumi-Noé, 1979) and has been constantly improved at Lund University’s Department of Building Science, Lund, Sweden. It currently runs on a PC in the Windows 95/NT environment (Kvist, 1997).

DEROB-LTH is a dynamic calculation program based on a Crank Nicolson method. The program uses a geometrical description of the building and internal solar radiation is distributed to various surfaces. Each surface is divided into 25 patches (5 horizontally and 5 vertically). The midpoint of each patch is used as a sensor determining the amount of solar radiation incident on the entire patch. Each building element (material) can contain a maximum of 7 internal and 2 external nodes and heat transfer is unidimensional in the program. Note, also, that only one air temperature is calculated for each volume (room).

The program contains 7 modules that can be executed separately. Information between the modules is transferred through an input-output data files system. This system saves calculation time since only specific modules must be activated again when data has been altered in the model for specific tasks.

In DEROB-LTH, the solar position at each hour is only calculated for the middle day of each month but the solar radiation intensity falling on different surfaces is calculated hour by hour (Wall, 1996). Solar radiation is divided into diffuse and direct radiation. Diffuse radiation is transmitted and spread diffusely while direct solar radiation is treated as direct until it meets an internal surface for the first time. Reflected radiation is assumed to be purely diffuse. Solar radiation can also be transmitted into adjoining rooms through windows between the rooms. If direct solar radiation is transmitted into the first volume and directly meets a glazed surface that faces another volume, some of the radiation is transmitted further as direct radiation.
Some other characteristics and assumptions of the program are as follows:

- Constant exterior air film coefficient.
- Variable internal convective heat transfer coefficient.
- No heat capacity for air.
- The sun is a point source.
- Longwave radiation in the volume is treated as an exchange between grey, diffuse surfaces.
- Sky, ground and ground reflected radiation is isotropic i.e. the intensity of the radiation beam is independent of the direction.

3.4.1.1 Improved window module in DEROB-LTH

The window model in DEROB-LTH has one temperature node in each pane and a variable window U-value (temperature-dependent, which affects convective and radiative heat transfer). Some assumptions of this module are that the pane resistance is zero, the pane absorptance is temperature independent and the view factor between the panes is unity as the distance between panes is usually insignificant compared with the area of the glazing (Källblad, 1998).

DEROB-LTH was recently supplemented with an improved window module. In this new module, the data for each individual pane can be entered as thickness, refraction and extinction coefficient or as 10° angle-dependent triplets (transmittance, reflectance front, and reflectance back). With the first data set, the Fresnel formalism is used to obtain accurate angular properties (Källblad, 1998). This formalism gives the reflected and transmitted amplitude components for the wavelength as functions of the optical constants of the media and the angle of incidence on the surface.

The Fresnel calculations used in the new DEROB-LTH version are valid for homogeneous i.e. uncoated glass. Coated glass, like reflective and low-e coated glazing used in this study, and tinted glass (uncoated) exhibit more complex behaviour. For coated glazing, multiple reflections within the coating’s very thin layers exhibit interference patterns (Källblad, 1998). Also, the optical properties of thin layers, only a few atomic layers thick, are different from the bulk properties (Furler, 1991). Roos (1997) suggests using a simple polynomial to predict the angular variation function of coated glazing accurately instead of complex exact Fresnel calculations. Polynomials by Roos were not, however, available at the time when this study was initiated. It should be noted that his work shows
that discrepancies between empirical and calculated (according to Fresnel equations) values for transmittance vary between 6-14% for angles of incidence between 45-75° for one glazing example.

A program called GLSIM based on multiplying matrices has also been developed by Pfrommer et al. (1995) for calculating the angular and wavelength-dependent properties of special glazing containing coated or tinted glass. This calculation program implies, however, that the wavelength material properties (refraction and absorption indices) of the individual coating layers are known or calculated backward from measurements of the spectral transmittance and reflectance at various wavelengths. These values may be difficult to obtain from the manufacturer for each coating layer. For tinted glazing, the discrepancies between measured and calculated values (with GLSIM) were as large as the discrepancies between angle-dependent transmittance values from clear and tinted glazing. The authors have, moreover, identified the need to validate GLSIM with high quality measurements made on glazing for which the precise composition is known.

Angular properties of multiple pane windows are calculated on the basis of single pane properties in the new DEROB-LTH version. The detailed procedure is described in Källblad (1998). Calculations of the solar angular optical properties of the glazing assemblies are, however, wavelength independent in the new program since solar, visible transmittance and reflectance usually given by manufacturers are normally derived by weighting the spectra with a standard terrestrial solar spectrum (Mecherikunnel, 1988 in Furler, 1991) or the sensitivity of the human eye (IES, 1984, in Furler, 1991). For common glazing materials, however, solar optical properties are roughly constant with wavelength and can be approximated by constant optical properties for all wavelengths, according to Arasteh et al. (1989). Furler (1991) showed that using a standard weighted wavelength method instead of a detailed wavelength dependent calculation method gives rise to errors of at most 1.5%.

Two-dimensional heat transfer at the glazing edges is not included in the new module and the exterior convective air film coefficient is a constant value since it is hard to obtain detailed data for wind speed in any climate. Some authors have shown that these approximations can introduce significant errors (Mc Cluney, 1991; Reilly et al., 1995). These aspects are, however, connected with convective and conductive heat transfer, which are of secondary importance here since they are assumed to be roughly constant amongst all the cases studied.

The angular dependency of optical properties is, thus, the central new feature of the new window module in DEROB-LTH. This detailed calculation procedure should allow higher levels of accuracy. It has been shown
that the traditional shading coefficient approach can over-predict the solar gain by up to 17% (for double-pane, clear glass) compared with a detailed, solar-angle dependent calculation method (Reilly et al., 1995).

### 3.4.2 WINDOW 4.1

In this study, the program WINDOW 4.1 was used to calculate the solar angle dependent optical properties (at 10° increments) of each glass. In the same way as the DEROB-LTH program, WINDOW 4.1 gives accurate angular properties for homogeneous i.e. uncoated glasses by applying Fresnel equations and Snell's law. For coated glazings, the angular properties are assumed to have the same relationship as either typical 1/8" (3 mm) clear glass (if the solar transmittance is greater than 65%) or typical 1/8" (3 mm) bronze glass (if the solar transmittance is less than 65%) (LBL, 1992). The angular properties were directly entered in the energy simulation program that subsequently calculated the properties for the whole glazing assemblies. This method was chosen since the information provided by the glazing manufacturer was limited to the transmittance and reflectance (front and back) measured for normal incidence.

WINDOW 4.1 uses the Solar Heat Gain Coefficient method, which is an angular and spectrally selective method. In the SHGC method, the solar gain of a glazing is determined on a wavelength-by-wavelength basis (ASHRAE, 1997). Note that the solar gain is the sum of the transmitted solar radiation (direct radiation from the sun and diffuse radiation from the sky and the ground) and solar radiation that is absorbed in the glass and re-emitted as heat in the room.

WINDOW 4.1 was also used to calculate the centre-of-glass U-value, shading coefficient, solar heat gain coefficient and optical properties at normal incidence presented in Table 3.4. The temperature distribution across the centre of the glazing system for a given set of environmental conditions is solved through an iterative technique that calculates an energy balance at each glazing surface (Arasteh et al., 1989). Heat transfer by combined conduction, convection and long-wave radiation is taken into consideration. Edge effects are accounted for by using a finite difference method9. Properties can, moreover, be calculated for various, constant environmental conditions (indoor-outdoor temperature difference, wind speed and direction, sky temperature and emissivity, etc.).

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9. These values are not presented in Table 3.4 since DEROB-LTH is purely unidimensional and, thus, cannot handle two-dimensional edge effects.
Note that WINDOW 4.1 has been validated experimentally and good agreement has been found between measured and calculated values (Arasteh, 1987 in Arasteh et al., 1989).
4 Results and discussion

4.1 Energy use

In this section, the glazings are named from A to H according to the convention presented in Table 3.4 (Section 3.2.1). Glazing A has the lowest SHGC while glazing H has the highest SHGC.

4.1.1 Hourly fluctuations

Before studying annual energy use, energy fluctuations were studied on an hourly basis during 2 cold and 2 warm weeks of the year to make sure that the internal loads and temperature set point schedules did not yield strange energy demand patterns. This analysis was carried out for only 2 glazings (A, H), 4 orientations (N, E, S and W), and an average $GWAR$ of 30%, in Lund.

Since the maximum average temperature (16.9°C) occurs in July and the minimum average temperature (0.8°C) is in March for 1988 (Wall, 1994), typical days during these months were chosen to represent extreme conditions during the year.

4.1.1.1 Hourly heating loads during cold weeks

Global solar radiation on a horizontal surface, outdoor temperatures and internal loads for the period March 5-18, 1988 are presented in Figures 4.1-4.3.
Figure 4.1  Global solar radiation on a horizontal surface (W/m²), Lund, March 5-18.

Figure 4.2  Outdoor temperature (°C), Lund, March 5-18.
Heating load curves for the period March 5-18 have been superposed to enhance peaks. Curves for glazings A and H orientated to the north are shown in Figures 4.4-4.5.

**Figure 4.3**  Internal loads (W), March 5-18.

**Figure 4.4**  Hourly heating load, Glazing A, North, 30% GWAR, Lund, March 5-18.
Figures 4.4 and 4.5 show the following:

- The highest peak occurred during weekends due to the absence of internal loads. The weekend peak load thus determines the size of the heating equipment. A different heating schedule should be set for weekends but, as mentioned before, DEROB-LTH-97.02 does not offer this possibility.

One way to model a variable weekday/weekend schedule in DEROB-LTH would be to run two separate sets of simulations for each case i.e. one with a variable 18/20°C heating schedule and one with a constant 18°C heating schedule at all times. Annual heating loads for weekends could subsequently be added to weekday loads on a calculation spreadsheet. This procedure would double the simulation time, however, since every case would have to be run twice. In this study, this procedure was avoided because one single heating schedule for all days of the week only yielded 4% more energy use annually in the worst case. Details of this estimate can be found in Appendix E.
Similar curves were obtained for both glazings. The loads were thus negligibly affected by solar radiation and a change in glazing transmittance has a minor effect on the heating load profile for this orientation. The temperature set points and the internal load schedule determine the heating load fluctuations on the north facade.

During weekdays, the heating load was strongly affected by internal loads. It increased continuously during the night and reached a peak at 07.00 hours. The load then dropped when the working day started at 08.00 hours. There was a small peak at 12.00 hours (internal loads drop to 240 W). The lowest load occurred during the afternoon, between 13.00-16.00 hours. During this period, the outdoor temperature is high, and internal loads and solar radiation contribute to reduce the load. The heating load increased after working hours.

During weekends, a higher demand in indoor temperature between 08.00-17.00 hours caused an increase in heating load during the day. The peak load was between 08.00-09.00 hours and the lowest load occurred at 17.00 hours when a sudden drop in indoor temperature was allowed.

Hourly fluctuations for heating with glazings A and H orientated towards south are presented in Figures 4.6-4.7.

![Figure 4.6](image-url)  
*Figure 4.6  Hourly heating load, Glazing A, South, 30% GWAR, Lund, March 5-18.*
Figures 4.6 and 4.7 show the following:

- As heating loads are more strongly affected by solar radiation for this orientation, it is harder to distinguish a repetitive pattern in the curves. This is especially true for glazing H, which has a higher solar transmittance. However, weekend and weekday peaks and drops occurred at the same hours as for the north orientation.

- For glazing H, little heating was needed in the afternoon to maintain the indoor temperature at 20°C. During this period, solar gains compensate for artificial heating.

A study of the hourly heating load fluctuations in March for east and west orientations showed similar trends as for north and south orientations. Peaks occurred at the same hours during the day i.e. around 07.00 hours for weekdays and 09.00 hours for weekends. The lowest loads occurred late in the afternoon i.e. around 16.00 hours during weekdays and around 17.00 hours during weekends. For all orientations, a small peak also occurred at lunchtime. The analysis showed that there should be a different heating temperature schedule for weekends. In the absence of such schedule, highest peaks occur outside the real “service” time of the building. The analysis also showed that setting the indoor temperature to increase
to 20°C before the beginning of the working day might result in very high heating peak loads in the morning since there is already a “natural” peak at 07.00 hours due to the absence of solar radiation and internal loads for the whole night combined with the lowest outdoor temperatures. This strategy may, however, provide higher levels of thermal comfort at the beginning of the working day.

4.1.1.2 Hourly cooling loads during warm weeks

Global solar radiation on a horizontal surface, outdoor temperatures and internal loads for the period July 4-17, 1988 are presented in Figures 4.8-4.10.

![Global solar radiation on a horizontal surface (W/m²)](image_url)

*Figure 4.8  Global solar radiation on a horizontal surface (W/m²), Lund, July 4-17.*
North:
Cooling loads and temperature fluctuations with glazing A facing north are presented in Figures 4.11-4.12.
Results and discussion

Figure 4.11  Hourly cooling load, Glazing A, North, 30% GWAR, Lund, July 4-17.

Figure 4.12  Hourly indoor temperature, Glazing A, North, 30% GWAR, Lund, July 4-17.
Figures 4.11 and 4.12 show the following:

- Unlike heating loads, the highest cooling loads occurred during weekdays. The weekday peaks thus determine the size of the cooling equipment.
- No cooling was required outside office hours and during weekends.
- Practically no cooling was required before 09.00 hours.
- For most days, cooling was only needed in the afternoon, between 13.00-16.00 hours. In the morning, the temperatures naturally stayed below 24°C, most of the time.
- Indoor temperatures dropped well below 24°C after the working day.

Cooling loads and temperature fluctuations with glazing H facing north are presented in Figures 4.13-4.14.

**Figure 4.13** Hourly cooling load, Glazing H, North, 30% GWAR, Lund, July 4-17.
Figures 4.13 and 4.14 show the following:

- Indoor temperatures and cooling loads were generally significantly higher with this glazing type than with glazing A.
- During weekdays, peak loads occurred at 16.00 hours on most days. This is also the time when the outdoor temperature is maximum (Fig. 4.9). A smaller peak occurred at 11.00 hours and the load decreased at 12.00 hours when internal loads dropped to 240 W.
- No cooling was needed outside office hours and during weekends.
- For some working days, high indoor temperatures occurred after working hours i.e. between 17.00-20.00 hours.

**South:**

Cooling loads and temperature fluctuations with glazing A facing south are presented in Figures 4.15-4.16.
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Figure 4.15  Hourly cooling load, Glazing A, South, 30% GWAR, Lund, July 4-17.

Figure 4.16  Hourly indoor temperature, Glazing A, South, 30% GWAR, Lund, July 4-17.
Figures 4.15 and 4.16 show the following:

- The peak demand for cooling occurred between 1400-1600 hours. A small peak occurred at 1100 hours and a small drop at 1200 hours.
- No cooling was required during the weekend, outside working hours, and in the morning for some working days.
- The maximum indoor temperature occurred at 1300 hours and the minimum temperature was around 0500 hours.
- Temperatures were well below 24°C before and after working hours.

Cooling loads and temperature fluctuations with glazing H facing south are presented in Figures 4.17-4.18.

**Figure 4.17** Hourly cooling load, Glazing H, South, 30% GWAR, Lund, July 4-17.
Figures 4.17 and 4.18 show the following:

- The cooling load for the south orientation is almost twice as high as that for the north orientation for the same glazing. The cooling load is also much higher for the high transmittance glazing than for the low transmittance glazing, for the south orientation.

- The peak in cooling load occurred between 14.00-15.00 hours. As for the north orientation, there was a small peak at 11.00 hours and a drop at 12.00 hours.

- Indoor temperatures were also much higher for the south than for the north orientation. This was especially the case at night, after working hours. The temperature rose above 24°C, reaching a maximum at 17.00 hours. The absolute minimum occurred around 05.00 hours.

- Contrary to the north orientation, some cooling was required during weekends, in the afternoon.

East:
Cooling loads and indoor temperatures with glazing A facing east are shown in Figures 4.19 and 4.20.
Results and discussion

Figure 4.19  Hourly cooling load, Glazing A, East, 30% GWAR, Lund, July 4-17.

Figure 4.20  Hourly indoor temperature, Glazing A, East, 30% GWAR, Lund, July 4-17.
Figures 4.19 and 4.20 show the following:

- Although morning loads and temperatures were generally high, the peak load still occurred in the afternoon, around 15.00-16.00 hours. There was a high peak at 11.00 hours (almost as high as the afternoon one).
- Weekends did not require cooling as temperatures naturally stayed below 24°C.
- Temperatures outside working hours were also well below 24°C and, for some days, no cooling was required in the morning.

Cooling loads and indoor temperatures for glazing H facing east are shown in Figures 4.21 and 4.22 below.

Figure 4.21 Hourly cooling load, Glazing H, East, 30% GWAR, Lund, July 4-17.
Figures 4.21 and 4.22 show the following:

- For glazing H, the peak load occurred in the morning, at 11.00 hours for some days. For other days, the peak occurred between 14.00-16.00 hours. The load dropped at 12.00 hours and rose after lunch but remained fairly constant throughout the afternoon and lower than the load at 11.00 hours in most cases.

- Indoor temperatures were high before the workday started since the sun faces the east facade in the morning. Temperatures also increased after working hours, which is surprising since the facade is in the shade at this time. Note that the rise in temperature is of course due to the fact that the cooling set point changes at 17.00 hours.

West:

Cooling loads and indoor temperatures for the west-facing room exhibited similar trends as for the south orientation except that the peak load occurred at the end of the day (16.00 hours) and was slightly higher than for the south orientation. For the high solar transmittance glazing, in-
door temperatures were much higher at night, which influenced morning loads that were also higher than for the south orientation. The west orientation resulted in the highest indoor temperature peaks.

Concluding remarks
The analysis of the hourly cooling loads and indoor temperature fluctuations for 2 typical warm weeks in July showed that peak loads usually occur late in the afternoon i.e. between 14.00-16.00 hours, except for the east orientation and the high solar transmittance glazing which yielded earlier peaks (11.00 hours and between 13.00-16.00 hours). The analysis also showed that the highest temperatures occurred at different times according to the type of glazing used. With glazing H, the temperature usually rose after working hours, reaching a peak between 17.00-20.00 hours. With glazing A, the highest temperatures occurred between 13.00-16.00 hours and the temperature dropped after working hours. The low solar transmittance glazing thus probably offers higher levels of thermal comfort than the high solar transmittance glazing. Generally, no cooling was needed outside office hours (before 08.00 hours and after 17.00 hours) on any warm day tested with both glazings since the indoor temperature stayed naturally below 28°C. Also, the low solar transmittance glazing eliminated the need for cooling during weekends for all orientations. Finally, for all orientations and types of glazing, the lowest temperatures occurred in the morning, between 04.00-06.00 hours.

4.1.2 Annual energy use
Although the climate was varied, Lund was the central climate used in most simulations. Thus, the glazing type and room orientation were initially varied with a constant glazing-to-wall area ratio (GWAR) of 30% in Lund. The GWAR was subsequently varied for 5 glazing types and 3 orientations in Lund. The climate was then changed for 3 glazing types with 2 GWAR and 3 orientations. A total of 5 climates were studied. The simulation scheme followed is described in Figure 4.23.
### Results and Discussion

<table>
<thead>
<tr>
<th>Glazing Type</th>
<th>LUND - 30% GWAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>N   NE E SE S SW W NW</td>
</tr>
<tr>
<td>B</td>
<td>N   NE E SE S SW W NW</td>
</tr>
<tr>
<td>C</td>
<td>N   NE E SE S SW W NW</td>
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<tr>
<td>D</td>
<td>N   NE E SE S SW W NW</td>
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<td>E</td>
<td>N   NE E SE S SW W NW</td>
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<tr>
<td>F</td>
<td>N   NE E SE S SW W NW</td>
</tr>
<tr>
<td>G</td>
<td>N   NE E SE S SW W NW</td>
</tr>
<tr>
<td>H</td>
<td>N   NE E SE S SW W NW</td>
</tr>
</tbody>
</table>

**Figure 4.23 Simulation scheme.**
4.1.2.1 Effect of the glazing type

The first series of simulations consisted of varying the glazing type and the orientation for a constant GWAR (30%) in Lund. The heating and cooling loads for each month and each glazing type are presented in Figures 4.24-4.27 for north and south orientations. It is assumed, as in all figures presented in this report, that the same amount of energy was used to produce 1 kWh of heat or 1 kWh of cooling.

![Heating load graph](image)

*Figure 4.24 Monthly heating load (kWh/m² month), North, 30% GWAR, Lund.*

![Cooling load graph](image)

*Figure 4.25 Monthly cooling load (kWh/m² month), North, 30% GWAR, Lund.*
Results and discussion

Figures 4.24-4.27 show the following:

- Heating loads were much larger than cooling loads for all glazing types and orientations.

Figure 4.26  Monthly heating load (kWh/m²/month), South, 30% GWAR, Lund.

Figure 4.27  Monthly cooling load (kWh/m²/month), South, 30% GWAR, Lund.
The cooling season extended from May to September on the north facade while it began in April and ended in October on the south facade. For both orientations and all glazings, heating was required from September to May inclusively. For some glazings (A, B), heating was required during the summer as well.

The glazing type had a larger effect on both heating and cooling loads on the south than on the north facade.

Annual heating and cooling loads for 8 glazings and for 4 orientations (N, E, S, and W) are presented in Figures 4.28-4.31.

![Annual energy use (kWh/m²/year), North, 30% GWAR, Lund.](image)
Results and discussion

Figure 4.29  Annual energy use (kWh/m²/year), East, 30% GWAR, Lund.

Figure 4.30  Annual energy use (kWh/m²/year), South, 30% GWAR, Lund.
Figures 4.28-4.31 show the following:

- For all orientations, the low-emissivity coated glazing (type F) yielded the lowest annual energy use while the reflective bronze glazing (type A) yielded high, if not the highest, annual energy use.

- The glazing type had the largest effect on annual energy use on the south facade. On this facade, a change in glazing affected heating by at most 27% and annual energy use by at most 10% (heating and cooling added in a 1:1 ratio). Cooling was affected by at most 86% by a change in glazing type (on the south-east facade). Note also that the effect of the glazing type on heating and annual energy use was small for north, east and west orientations. The smallest effect of a change in glazing type was 11% for heating, 80% for cooling and 4% for annual energy use.

- On the north and south facades, higher solar transmittance glazing (F to H) yielded lower annual energy use while on the east and west facades, average solar transmittance glazing (C to F) resulted in lower annual energy use.
On the south and north facades, higher solar gains during the winter more than compensate for larger cooling loads resulting from higher solar transmittance glazing. On the east and west facades, the winter solar gains are not sufficient to compensate for the large increases in cooling generated by high solar transmittance glazing.

4.1.2.2 Effect of orientation

Incremental heating and cooling loads for all glazing types tested with 30% GWAR, in Lund are presented as a function of orientation in Figure 4.32.

![Figure 4.32 Incremental annual energy use (kWh/m²year), 30% GWAR, Lund.](image)

Figure 4.32 shows the following:

- The orientation had the largest effect on energy use with high solar transmittance glazing H. Changing the orientation affected heating by at most 23%, cooling by at most 58% and annual energy use by at most 12% with this glazing type.

10. The incremental cooling load is the difference between the cooling load for one glazing in one orientation and the smallest cooling load amongst all glazing types and orientations. The incremental heating load is the difference between the heating load for one glazing in one orientation and the highest heating load amongst all glazing types and orientations. This allows the representation of the effect of glazing type and orientation on both cooling and heating loads on the same figure.
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- Glazing A was negligibly affected by a change in orientation. The smallest effect of a change in orientation was 6% for heating, 41% for cooling and 5% for annual energy use with this glazing.

- Cooling loads were almost constant from east to west while heating loads varied significantly from east to south and from south to west. Thus, while heating loads were significantly reduced by a change in orientation from east to south and from west to south, cooling loads remained fairly constant for all these orientations. This explains why high solar transmittance glazing is preferable on the south orientation while average transmittance glazings yield lower annual energy use on east and west orientations. As discussed in previous sections, the large reductions in heating loads on the south facade that occur with high solar transmittance glazing more than compensate for the large increases in cooling. This is not the case on east and west facades where the reductions in heating are not sufficient to offset the large cooling loads due to high transmittance glazing.

Annual heating and cooling loads have been added (in a 1:1 ratio) and plotted as a function of orientation for some of the glazings studied (A, C, D, F, H), with 30% GWAR, in Lund. This plot is presented in Figure 4.33 below.

Figure 4.33 Annual energy use (kWh/m²/year), 30% GWAR, Lund.
Results and discussion

Figure 4.33 shows the following:

- As mentioned in the previous section, south and north orientations had a lower annual energy use with high solar transmittance glazing (F to H) while average transmittance glazing (C to F) performed better on east and west facades.
- Glazing A yielded high annual energy use while glazing F yielded the lowest annual energy use for all orientations. Glazing F seems to have an “optimal” SHGC for this climate.

4.1.2.3 Effect of glazing-to-wall area ratio (GWAR)

In a second series of simulations, the glazing-to-wall area ratio (GWAR) was varied for 5 glazings, and 3 orientations (N, E, and S) in Lund. The west orientation was eliminated since the previous results (sections 4.1.2.1 and 4.1.2.2) indicated that monthly and annual energy use trends for east and west were similar. The incremental annual energy use as a function of GWAR for the 5 glazings and 3 orientations tested is shown in Figures 4.34-4.36.

![Figure 4.34 Incremental annual energy use (kWh/m²/year), North, Lund.](image-url)
Figure 4.35  Incremental annual energy use (kWh/m²/year), East, Lund.

Figure 4.36  Incremental annual energy use (kWh/m²/year), South, Lund.
Figures 4.34-4.36 show the following:

- TheGWAR had a larger impact on south than north and east facades. On this facade, a change in GWAR affected heating by at most 48%, cooling by at most 98% and annual energy use by at most 18%. Note that the largest impact was always with glazing F since the 70% GWAR was studied with this glazing. The impact of a change in GWAR on heating loads and energy use was negligible for glazing A (~0%), on the north façade. However, cooling was affected by 57% with a change in GWAR on this facade with this glazing type.

- Increasing the GWAR generated an increase in cooling and a reduction in heating loads. On the north façade, the increase in cooling was approximately equal to the reduction in heating for a given GWAR. On the south façade, the reduction in heating was larger than the increase in cooling for all glazings but glazings F and H where the increase in cooling was approximately equal to the reduction in heating. On the east façade, increasing the GWAR resulted in larger increases in cooling than reductions in heating.

  This observation supports the comments made in the previous sections: on the east façade, an increase in solar gains due to an increase in glazing solar transmittance or GWAR generates larger increases in cooling than reductions in heating thus resulting in higher annual energy use. Thus, lower transmittance or smaller GWAR are desirable on east (and thus west) façades than on south and north.

Figure 4.37 shows the incremental annual energy use as a function of the solar aperture. The solar aperture (SA) is defined by Sullivan et al. (1992) as the product of the shading coefficient (SC) and the window-to-wall area ratio. In this study, the SA is the product of the SC and the GWAR. This number gives an indication of the total amount of solar radiation entering the room.
Figure 4.37 shows that:

- The impact of the GWAR on cooling loads was similar for east and south orientations while the reductions in heating loads due to an increase in GWAR was significantly greater on the south than on the east facade. Results thus indicate that larger GWAR or higher glazing transmittance should be used on the south than on the east facade as demonstrated previously.

- For the north orientation, increasing the GWAR reduced heating loads and increased cooling loads by approximately the same amount.

In Figure 4.38, heating and cooling loads have been added in a 1:1 ratio and plotted as a function of the solar aperture.
Figure 4.38 shows that:

- When heating and cooling loads are summed, annual energy use was minimum at solar apertures around 0.2 on the south facade, around 0.12 on the east facade, and between 0.2-0.3 on the north facade. Thus, in Lund, the optimum GWAR for south-orientated office rooms was 22% for clear glass, 30% for low-e coated glass (SC=0.63) and over 40% for average transmittance reflective and absorbing glass (SC=0.44-0.48), etc. For east-orientated (and west-orientated) rooms, the optimum GWAR was 14% for clear glass, 19% for the low-e coated glass and around 25% for average transmittance glazing (SC=0.44-0.48). On the north facade, the optimum GWAR was 23-34% for clear glass, 32-48% for low-e coated glass (SC=0.63) and 42-68% for average transmittance solar-protective glazing (SC=0.44-0.48).

The results thus indicate that solar-protective glazing should only be used with large glazing areas (> 40%) on north and south facades but can be energy-efficient with GWAR around 25% on east (and west) facades. Smaller GWAR or lower SC should thus preferably be used on the east facade than on the south facade.

- The north facade was negligibly affected by a change in SA. Energy use for north orientated rooms is thus negligibly affected by the glazing optical properties and area since the trend is not as clear as for the other orientations. Nevertheless, annual energy use seems to mini-
mise at rather high $SA$ i.e. around 0.2-0.3. This indicates that north orientations can profit from having large windows as long as higher thermal losses through a larger window area are compensated for by a lower $U$-value for the rest of the building envelope and/or for the window itself. It appears that diffuse radiation incident on north-orientated windows in the winter can contribute to a reduction in the heating demand.

4.1.2.4 Effect of climate

In a third series of simulations, the climate was varied for 3 orientations (N, E, and S), 3 glazing types (A, D and F) and 2 $GWAR$ (20%, 50%). The climates tested were Lund, Stockholm, and Luleå (Sweden), Oslo (Norway) and Montreal (Canada). Glazing types were chosen so that large (50%) and small (20%) $GWAR$ would be studied. Also, an attempt was made to include a range of $SC$ values as well as all the main categories of glazings (reflective, absorbing and low-e). Glazing A was eliminated for 50% $GWAR$ since it was impossible to keep the thermal losses constant for this case (see Appendix A).

Results of annual energy use for the small $GWAR$ (20%) are presented in Figures 4.39-4.43.

![Figure 4.39](image-url)  
*Figure 4.39  Annual energy use (kWh/m²/year), 20% $GWAR$, Lund.*
Results and discussion

**Figure 4.40** Annual energy use (kWh/m²/year), 20% GWAR, Stockholm.

**Figure 4.41** Annual energy use (kWh/m²/year), 20% GWAR, Luleå.
**Figure 4.42** Annual energy use (kWh/m²/year), 20% GWAR, Oslo.

**Figure 4.43** Annual energy use (kWh/m²/year), 20% GWAR, Montreal.
Figures 4.39-4.43 show the following:

- The highest annual energy use was in Luleå. Montreal came second with higher annual energy use than Stockholm and Oslo, which had similar energy use patterns. Lund had the lowest annual energy use. Note that for this GWAR (20%), a change in climate affected heating by at most 48%, cooling by at most 80% and annual energy use by at most 46%. The smallest effect of a change in climate was 45% for heating, 28% for cooling and 40% for annual energy use.

  High annual energy use in Montreal is due to a combination of high heating loads (higher than in Stockholm and Oslo) resulting from low outdoor temperatures in the winter (see Fig. 3.4) and high cooling loads (higher than in Sweden) resulting from the high solar radiation intensity (Table 3.6).

- The cooling demand was approximately the same in all the Swedish cities tested despite the fact that Lund, Stockholm and Luleå are located far away from each other, in the south, centre and north of Sweden.

- Both orientation and glazing type affected energy use more significantly in Montreal than in the three Swedish cities and in Oslo because there is significantly more solar radiation in Montreal than in Lund, Stockholm, Luleå and Oslo; the glazing choice and orientation are thus crucial issues in the Canadian city.

- In all the climates tested, the south orientation had the lowest annual energy use.

- Although the glazing type affected annual energy use in a negligible manner on the north and east orientations, glazing F yielded the lowest annual energy use on the east and north facades, in most cases.

- The choice of glazing had a more significant impact on annual energy use on the south facade, especially in Montreal. The impact of glazing type was relatively low in Luleå.

- In Montreal where the effect of glazing type and orientation was the greatest, changing the glazing type reduced heating loads by at most 24%. Cooling loads were reduced by at most 47% and annual energy use by at most 18% due to a change in glazing type (on the south facade). In the same city, changing the orientation reduced heating loads by at most 25% and reduced cooling loads by at most 38%. The annual energy use was reduced by at most 20% by a change in orientation.
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- In Luleå, where the relative impact of glazing type and orientation was the smallest, changing the glazing type reduced heating by at most 11%. Cooling was reduced by at most 62% and annual energy use by at most 8% by a change in glazing type. In the same city, a change in orientation reduced heating loads by at most 9% while cooling was reduced by at most 43%. A change in orientation affected annual energy use by at most 7% in Luleå.

Results thus indicate that the impact of glazing type on heating was greater in Montreal than in Luleå but the impact of glazing type on cooling was greater in Luleå than in Montreal. Montreal receives enough solar radiation in the winter so that the glazing solar transmittance or orientation can influence heating loads significantly. Luleå is above the Arctic Circle. Thus, sunshine hours are very limited during the winter in this Swedish town. On the other hand, the sun practically never sets in Luleå during the summer. Thus, the glazing solar transmittance and orientation become key issues in this northern city during summer time. The cooling season is, however, short and cooling represents a negligible part of annual energy loads.

Note also, that the impact on heating and annual energy use due to a change in orientation and a change in glazing type was approximately of the same magnitude while cooling was more affected by the glazing type than by the orientation. This means that the glazing type is a key issue, before orientation, for cooling, while orientation and glazing type have an equal impact on heating loads, in both cities.

Annual energy use totals for the large GWAR (50%) are presented in Figures 4.44-4.48 for 2 glazing types, and 3 orientations in the 5 cities tested.
Results and discussion

Figure 4.44  Annual energy use (kWh/m²/year), 50% GWAR, Lund.

Figure 4.45  Annual energy use (kWh/m²/year), 50% GWAR, Stockholm.
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Figure 4.46 Annual energy use (kWh/m²/year), 50% GWAR, Luleå.

Figure 4.47 Annual energy use (kWh/m²/year), 50% GWAR, Oslo.
Figures 4.44-4.48 show the following:

- Luleå still had the highest annual energy use compared with the other cities. However, Montreal and Stockholm had similar loads for some orientations. As in the previous case, Stockholm and Oslo had very similar trends in energy use. Lund had the smallest annual energy use. For this GWAR (50%), a change in climate affected heating loads by at most 57%, cooling loads by at most 42% and annual energy use by at most 44%. The smallest effect of a change in climate was 45% for heating, 28% for cooling and 40% for annual energy use.

- With a larger GWAR, the impact of orientation on annual energy use was larger, especially in Montreal where increasing the GWAR from 20 to 50% reduced heating loads by 44% and almost tripled the cooling loads, resulting in annual energy use 13% lower on the south facade, with glazing F.

- An increase in GWAR resulted in significant increase in cooling loads, and also resulted in a general reduction in heating loads, especially for the south orientation. In Montreal and Luleå, increasing the GWAR generally resulted in a reduction in annual energy use, especially on the south facade. In Stockholm, Oslo and Lund, annual energy use was actually increased with an increase in GWAR on the east facade.
Glazing D (average transmittance) was the best option in Lund, Stockholm and Oslo, especially on the south and east facades. The east orientation yielded very high annual energy loads (larger than the north orientation) because of the large cooling loads resulting from large GWAR. South had the lowest annual energy use. Note that the difference between glazings D and F was, however, relatively small.

For the 50% GWAR, glazings D and F (average and high transmittance) performed approximately in the same way in Montreal and Luleå. These results thus indicate that in sunny cold climates like Montreal and Luleå, optimal GWAR may be larger and optimal glazing solar transmittance higher than in more temperate and cloudy climates like Lund, Stockholm and Oslo because there is a larger potential for solar utilisation during the winter and because heating loads are significant.

With 50% GWAR, changing the glazing type affected heating loads by at most 29% and cooling loads by at most 41% in Montreal. However, the impact of a change in glazing type on annual energy use was only 3-4%. In the same city, a change in orientation reduced heating by at most 55% and cooling by at most 60%. Annual energy use was affected by at most 30% by changing the orientation.

In Luleå, a change in glazing type affected heating by at most 10% and cooling by at most 45%. Annual energy use was reduced by at most 3% by changing the glazing type. A change in orientation resulted in reductions in heating of at most 18% and cooling of at most 62% while annual energy use was reduced by at most 9% in Luleå.

Although it appears that a change in orientation has a larger effect on energy use than a change in glazing type, it should be remembered that only 2 glazing types were tested for the 50% GWAR.

4.1.3 Peak loads

The simulation of the annual energy demand for different cities (section 4.1.2.4) showed that large fluctuations occurred in Montreal when the glazing properties and orientation were varied. Montreal was thus chosen along with Lund for a comparison of peak loads. For this purpose, heating and cooling loads were analysed on an hourly basis for one whole year for all glazing types with 30% GWAR orientated south. Weekends were eliminated from the peak load analysis for heating since it was shown before (section 4.1.1.1) that weekend loads were higher than weekday loads.
loads when only one heating schedule was used for all days of the week. This situation is unlikely to occur in a real building where the heating schedule should be adapted to a normal working schedule.

In order to identify general trends, heating and cooling loads were plotted as a function of time (hour). These plots are not presented here as they consist of a large amount of data. Instead, the trends identified during this analysis are summarised in Table 4.1 below.

Table 4.1 General trends for peak loads, south orientation.

<table>
<thead>
<tr>
<th>City</th>
<th>End-use</th>
<th>Glazing type</th>
<th>Period</th>
<th>Peak load (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lund</td>
<td>heating</td>
<td>A</td>
<td>Sept. to March</td>
<td>07.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>April</td>
<td>04.00-07.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>Oct. to March</td>
<td>07.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>April</td>
<td>06.00-07.00</td>
</tr>
<tr>
<td>Montreal</td>
<td></td>
<td>A</td>
<td>Nov. to March</td>
<td>07.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Sept., Oct. and April, May</td>
<td>05.00-07.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>Nov. to March</td>
<td>07.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Oct.</td>
<td>06.00-07.00</td>
</tr>
<tr>
<td>Lund</td>
<td>cooling</td>
<td>A</td>
<td>June to August</td>
<td>13.00-16.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>May, Sept.</td>
<td>16.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>April to Nov.</td>
<td>13.00-16.00</td>
</tr>
<tr>
<td>Montreal</td>
<td></td>
<td>A</td>
<td>June to Sept.</td>
<td>13.00-16.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>H</td>
<td>June to Sept.</td>
<td>13.00-16.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Other</td>
<td>16.00</td>
</tr>
</tbody>
</table>

In Lund, heating was required all round the year with glazing A but the “real” heating season (more than isolated hours) was from September to May for this glazing type. The cooling season extended from May 12th to September 9th. With glazing H, no heating was necessary in July and August and the “real” heating season was from October to March. The cooling season started on April 7th and ended on November 8th.

In Montreal, with glazing A, no heating was necessary in July and August and very little was required in June. The “real” heating season was from September to May as in Lund. The cooling season started on May
5\textsuperscript{th} and ended on October 8\textsuperscript{th}. With glazing H, no heating was required in July, August and September and very little was required in June. The “real” heating season extended from October to March while the cooling season started on February 18\textsuperscript{th} and ended on December 2\textsuperscript{nd}.

Table 4.1 shows that the highest heating load occurred in the morning, before working hours in both cities and for both types of glazing for the south orientation. The peak load occurred at 07.00 hours during the coldest period of the year in Lund and Montreal. However, during the spring and autumn, peaks occurred earlier i.e. between 04.00-07.00 hours.

Table 4.1 also shows that the cooling peak load occurred between 13.00-16.00. Some months in the autumn and spring had a peak around 16.00 hours almost every day. Note, however, that the calculation in DEROB-LTH ignores summer time and that this factor was also neglected during the analysis. In Sweden and Canada in the summer time, which is usually from the end of March to the end of October, people start and finish working one hour earlier (compared with the solar time). Thus, the workday in this study would be from 07.00-16.00 hours. This means that the working schedule is asymmetrical with respect to the sun and that more hours are “worked” earlier in the day. This is illustrated in Figure 4.49 for one day in the middle of the summer (July 15) and for a south-orientated room. Since most of the high peaks occur towards the end of the day for this orientation, it can be speculated that the summer schedule has a positive effect on energy use and peak loads since the end-of-day high peaks can be avoided. This might also be true for the west facing rooms. Note also that one more hour is “worked” early in the morning when the solar radiation intensity is low. This certainly allows the saving of some energy on south and west facades. For east orientated rooms, however, the summer time means that more hours are “worked” while the sun faces the facade. East-orientated rooms might thus have a higher cooling demand due to the summer work schedule.

The highest annual load and corresponding climatic conditions are presented in Table 4.2 for Lund, for the south orientation and different glazings.
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Figure 4.49 Sun position in Lund on July 15 and work schedule.

Table 4.2 Highest annual load and corresponding climatic conditions, Lund, South.

<table>
<thead>
<tr>
<th>Glazing</th>
<th>Highest load (Wh/hm²)</th>
<th>Date</th>
<th>Time</th>
<th>Outdoor Temperature (°C)</th>
<th>Global solar radiation (horizontal) (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Heating: 43.3</td>
<td>November 21</td>
<td>07.00</td>
<td>-8.7</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Cooling: 26.8</td>
<td>June 9</td>
<td>14.00</td>
<td>+27.0</td>
<td>667.7</td>
</tr>
<tr>
<td>B</td>
<td>Heating: 41.7</td>
<td>November 21</td>
<td>07.00</td>
<td>-8.7</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Cooling: 34.6</td>
<td>August 10</td>
<td>15.00</td>
<td>+24.4</td>
<td>652.6</td>
</tr>
<tr>
<td>C</td>
<td>Heating: 40.7</td>
<td>March 15</td>
<td>07.00</td>
<td>-7.7</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>Cooling: 40.9</td>
<td>August 10</td>
<td>15.00</td>
<td>+24.4</td>
<td>652.6</td>
</tr>
<tr>
<td>D</td>
<td>Heating: 40.8</td>
<td>March 15</td>
<td>07.00</td>
<td>-7.7</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>Cooling: 40.7</td>
<td>August 10</td>
<td>15.00</td>
<td>+24.4</td>
<td>652.6</td>
</tr>
<tr>
<td>E</td>
<td>Heating: 40.7</td>
<td>March 15</td>
<td>07.00</td>
<td>-7.7</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>Cooling: 46.7</td>
<td>August 10</td>
<td>15.00</td>
<td>+24.4</td>
<td>652.6</td>
</tr>
<tr>
<td>F</td>
<td>Heating: 39.6</td>
<td>March 15</td>
<td>07.00</td>
<td>-7.7</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>Cooling: 54.3</td>
<td>August 10</td>
<td>15.00</td>
<td>+24.4</td>
<td>652.6</td>
</tr>
<tr>
<td>G</td>
<td>Heating: 39.6</td>
<td>March 15</td>
<td>07.00</td>
<td>-7.7</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>Cooling: 59.5</td>
<td>August 10</td>
<td>15.00</td>
<td>+24.4</td>
<td>652.6</td>
</tr>
<tr>
<td>H</td>
<td>Heating: 39.3</td>
<td>March 15</td>
<td>07.00</td>
<td>-7.7</td>
<td>19.1</td>
</tr>
<tr>
<td></td>
<td>Cooling: 67.4</td>
<td>August 10</td>
<td>15.00</td>
<td>+24.4</td>
<td>652.6</td>
</tr>
</tbody>
</table>
For most glazings, the highest heating load occurred on March 15th, at 07.00 hours. At this time, there were no internal loads in the building, the outdoor temperature was relatively low (−7.7°C) and there was very little solar radiation (19.1 W/m²). The highest cooling load occurred, for most glazings, on August 10th, at 1500 hours. At this time, internal loads were maximal (330 W), outdoor temperature was fairly high (24.4°C) and solar radiation was also high (652.6 W/m²). Note that these hours may not represent extreme climatic conditions for the year as shown by the conditions given for November 21, for instance (Table 4.2). The highest load that occurred on March 15 is the result of the climatic conditions prevailing during the hours preceding the peak.

The highest annual load and corresponding climatic conditions in Montreal are presented in Table 4.3 for the south orientation and different glazings.

Table 4.3 Highest annual load and corresponding climatic conditions, in Montreal, South.

<table>
<thead>
<tr>
<th>Glazing</th>
<th>Highest load (Wh/m²)</th>
<th>Date</th>
<th>Time</th>
<th>Outdoor Temperature (°C)</th>
<th>Global solar radiation (horizontal) (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Heating 81.0</td>
<td>January 27</td>
<td>03.00</td>
<td>-30.5</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Cooling 46.5</td>
<td>July 21</td>
<td>14.00</td>
<td>32.4</td>
<td>834.3</td>
</tr>
<tr>
<td>B</td>
<td>Heating 78.2</td>
<td>January 19</td>
<td>07.00</td>
<td>-29.4</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>Cooling 52.0</td>
<td>July 21</td>
<td>14.00</td>
<td>32.4</td>
<td>834.3</td>
</tr>
<tr>
<td>C</td>
<td>Heating 75.8</td>
<td>January 19</td>
<td>07.00</td>
<td>-29.4</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>Cooling 54.0</td>
<td>July 21</td>
<td>14.00</td>
<td>32.4</td>
<td>834.3</td>
</tr>
<tr>
<td>D</td>
<td>Heating 75.8</td>
<td>January 19</td>
<td>07.00</td>
<td>-29.4</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>Cooling 54.0</td>
<td>July 21</td>
<td>14.00</td>
<td>32.4</td>
<td>834.3</td>
</tr>
<tr>
<td>E</td>
<td>Heating 75.8</td>
<td>January 19</td>
<td>07.00</td>
<td>-29.4</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>Cooling 57.5</td>
<td>July 21</td>
<td>14.00</td>
<td>32.4</td>
<td>834.3</td>
</tr>
<tr>
<td>F</td>
<td>Heating 74.4</td>
<td>January 19</td>
<td>07.00</td>
<td>-29.4</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>Cooling 60.2</td>
<td>July 21</td>
<td>14.00</td>
<td>32.4</td>
<td>834.3</td>
</tr>
<tr>
<td>G</td>
<td>Heating 72.9</td>
<td>January 19</td>
<td>07.00</td>
<td>-29.4</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>Cooling 61.9</td>
<td>July 21</td>
<td>14.00</td>
<td>32.4</td>
<td>834.3</td>
</tr>
<tr>
<td>H</td>
<td>Heating 72.5</td>
<td>January 19</td>
<td>07.00</td>
<td>-29.4</td>
<td>18.9</td>
</tr>
<tr>
<td></td>
<td>Cooling 68.4</td>
<td>October 13</td>
<td>15.00</td>
<td>18.6</td>
<td>532.8</td>
</tr>
</tbody>
</table>
In Montreal, the highest heating load occurred on January 19th, at 07.00 hours, for most glazings. At this moment, there were no internal loads in the building, the outdoor temperature was fairly low (-29.4°C) and the solar radiation was almost nil (18.9 W/m²). In the same city, the highest cooling load occurred on July 21st, at 14.00 hours, for most glazings. At this time, internal loads were maximal (330 W), the outdoor temperature was fairly high (32.4°C) and solar radiation intensity was high (834.3 W/m²). Note that, as in the case of Lund, peaks tend to occur on different days for extreme glazings (A, B or H, for example). These glazings have either very low or very high solar transmittance meaning that the solar radiation factor has more or less influence on the hourly loads. For example, the highest cooling load in Montreal and glazing H occurred on October 13th instead of July 21st as for all other glazings despite much less extreme climatic conditions. This might be the result of an extremely low solar altitude combined with a very high solar transmittance glazing (thus more solar radiation is admitted in the building).

The highest peaks for heating and cooling for Lund and Montreal are compared in Figures 4.50-4.51.
Figure 4.50 shows that the peaks for heating were almost twice as high in Montreal as in Lund. The figure also shows that the glazing transmittance had a small impact (at most 11%) on peaks in both cities. This is easily explained by the fact that peaks occur when there is almost no solar radiation incident on the windows.

For cooling, the situation was completely different as shown by Figure 4.51. Peak loads increased as the glazing transmittance increased, especially in Lund where a change in glazing transmittance reduced the peak load by up to 61%. In Montreal, the maximum effect of a change of glazing on peak cooling was only 32%. Figure 4.51 also shows that for low solar transmittance glazing (A, B), the peak was almost twice as high in Montreal as in Lund while for high transmittance gluazings (G, H) peaks were almost equal in both cities.

4.2 Indoor temperatures

Indoor temperatures were also briefly analysed for all glazings included in the study with 30% GWAR orientated towards the south in Lund and Montreal. No cooling system was used for these simulations and, thus, indoor temperatures fluctuated according to climatic conditions and gla-
Results and discussion

The number of hours per year within each temperature interval above 28°C (the comfort zone limit) was computed for each glazing option in both climates. Only hours falling within the working schedule were selected for the analysis. Hours with heating were removed since, for these hours, the temperature was artificially controlled by the heating system. Results of the simulations are presented in Figures 4.52-4.54 below. Figure 4.54 shows the total number of hours when the indoor temperature was above 28°C for each glazing in both climates.

Figure 4.52  Hours within temperature intervals (°C) for 8 glazing types, South, 30% GWAR, Lund.
Figure 4.53  Hours within temperature intervals (°C) for 8 glazing types, South, 30% GWAR, Montreal.

Figure 4.54  Hours with indoor temperatures above 28°C, South, 30% GWAR, Lund and Montreal.
Figures 4.52-4.54 show the following:

- In Lund, there were no hours with indoor temperatures higher than 35.9°C while in Montreal, temperatures up to 37.9°C were reached with glazing H.

- In Lund, the indoor temperature was under 28°C almost all the time with glazing A meaning that this glazing can avoid the use of a cooling system. In Montreal, even with glazing A, a large number of hours (306) had indoor temperatures above 28°C. Hours above the comfort limit or “cooling” hours represented between 306-737 “working” hours i.e. between 2 and 4 “working” months, depending on the glazing type. This analysis thus indicates that cooling is mandatory in Montreal. Results also indicate that changing the glazing type in Montreal could reduce the number of hours with indoor temperature above 28°C by 50%.

- Figure 4.54 shows that the glazing type seems to have a larger effect on indoor temperatures in Lund than in Montreal. In Montreal, outdoor temperatures in the summer are higher than in Lund. Thus, the glazing solar transmittance might be a secondary factor affecting indoor temperatures and, in turn, cooling loads.

- In both cities, increasing the glazing transmittance resulted in more hours above the comfort limit except for glazing D (absorbing glass) which performed better than glazing C (reflecting glass) despite a slightly higher transmittance and a higher $SHGC$. The difference between the two glazings was, however, small.
5 Conclusions

5.1 Solar-protective glazing for cold climates

5.1.1 Conclusions from the hourly fluctuations analysis

The analysis of hourly fluctuations in Lund for cold and warm weeks showed that peaks and troughs for heating and cooling are “reversed” i.e. the highest heating load occurred at the time of the lowest cooling load and vice versa. Thus, peak heating occurred early in the morning, most often at 07.00 hours. The lowest load was in the afternoon i.e. between 13.00-16.00 hours. In contrast, peak cooling occurred in the afternoon between 13.00-16.00 hours while the lowest load was usually early in the morning before the beginning of the working day.

The study also indicated that peaks and troughs tend to occur around the same time regardless of the orientation and glazing type, except for one case i.e. the east orientation and glazing H where peak cooling occurred around 11.00 hours. In general, however, cooling loads were highest in the afternoon for all cases. Cooling peaks were also maximal for the west orientation, which suggests that the summer time used in Sweden (and Canada) is an energy-efficient measure since it allows skipping one hour of afternoon solar radiation. The study also suggests that glazing (or shading) strategies are especially important for the afternoon sun, and the west orientation.

An analysis of hourly cooling loads also showed that cooling was almost never required outside working hours thus suggesting that allowing a temperature rise when the building is not used is an energy-efficient measure. Internal loads should also be reduced as much as possible by using energy-efficient equipment, for example.

One important finding was that using only one temperature set point schedule for heating for every day of the week including weekends had the result that the highest peaks occurred during the weekends when there is no “free” heat available in the building. In this case, the equipment is
sized according to weekend loads, outside the useful “service time” of the building. The study thus suggests that, in real buildings, the indoor temperature should be allowed to drop during weekends when the building is not occupied. The savings in annual energy use were estimated to be at most 4% but additional benefits like a reduction in equipment sizing may be worth the effort of setting a different heating schedule for weekends. Similarly, simulation programs like DEROB-LTH should offer the possibility to model different heating schedules for different days of the week. The next version of DEROB-LTH, which will be released at the end of 1998, will include these types of schedules.

The analysis also indicated that setting the indoor temperature to increase to 20°C before the beginning of the working day might result in very high heating peak loads in the morning since there is already a “natural” peak at 07.00 hours due to the absence of solar radiation and internal loads for the whole night combined with the lowest outdoor temperatures. This strategy may, however, provide higher levels of thermal comfort at the start of the working day.

5.1.2 Conclusions from the annual energy use analysis

In general, results indicate that the heating demand was many times larger than the cooling demand, with all glazing types, orientations, glazing areas and climates. Also, increasing the glazing transmittance or GWAR generally contributed to reductions in heating loads and increases in cooling loads in all cases. The annual energy demand was reduced or increased as a function of the respective reduction in heating and increase in cooling loads for each case.

In general, the low-emissivity coated glazing (type F) always yielded low, if not the lowest, annual energy use, in all the cases and cities tested. In most cases, this glazing reduced heating almost as much as glazings G and H while increasing cooling loads less than these glazing types, thus resulting in lower annual energy use. Glazing F seems to have an “ideal” SHGC for the climates tested in this study. This is an interesting finding since this glazing is mostly used in cold climates for other purposes i.e. to reduce heat losses through a reduction of secondary radiation to the outside by applying a low-emissivity coating on the glass.

Another general observation was that the low transmittance reflective bronze glazing (type A) almost always yielded much higher annual energy use than all other glazing types although it reduced cooling significantly. Its use is thus not recommended in cold climates. However, for
buildings that are not equipped with a cooling system, low solar transmittance glazings (A, B) were the only glazings that provided acceptable indoor temperatures in the summer in Lund.

5.1.2.1 Effect of glazing type

Results indicate that the glazing type generally had a more significant effect on the heating and annual energy demand on the south facade than for other orientations. However, the cooling demand was more significantly affected by a change in glazing type on the south-east facade. The impact of a change in glazing type on heating and annual energy use was small for other orientations, with 30% GWAR, in Lund. Note, however, that cooling was affected by at least 80% by a change in glazing type. Overall, a change in glazing type affected heating by 11-27%, cooling by 80-86% and annual energy use (heating + cooling) by 4-10% with 30% GWAR, in Lund.

Table 5.1 Impact of a change in glazing type on energy use, 30% GWAR, Lund.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Impact of a change in glazing type on energy use</th>
</tr>
</thead>
<tbody>
<tr>
<td>South</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>11-27% heating</td>
</tr>
<tr>
<td></td>
<td>80-86% cooling</td>
</tr>
<tr>
<td></td>
<td>4-10% annual</td>
</tr>
<tr>
<td>North</td>
<td>small</td>
</tr>
<tr>
<td>East</td>
<td></td>
</tr>
<tr>
<td>West</td>
<td></td>
</tr>
</tbody>
</table>

One important finding is that the optimum glazing solution was orientation-dependent. On south and north orientations, high transmittance glazing (F to H) yielded lower annual energy use than all other glazings while on east and west orientations, average transmittance glazings (C to F) yielded lower annual energy use, with 30% GWAR, in Lund (see Table 5.2). However, the low-e coated glazing (type F) performed well on all facades while the low solar transmittance reflective glazing (type A) yielded high or the highest annual energy use for all orientations. On the south facade, large solar gains in the winter due to high transmittance glazing more than offset increases in cooling. On east and west facades, the cooling load was increased in the same fashion as on the south facade.
Solar-Protective Glazing for Cold Climates

but heating was not reduced enough to offset increases in cooling. On the north facade, higher transmittance glazing produced a slightly higher cooling load that was easily offset by a small reduction in heating resulting from higher transmittance glazing. Note that the north facade is never exposed to direct solar radiation during the winter. Thus, the reductions in heating obtained are mostly due to diffuse radiation.

Table 5.2 Optimum glazing type as a function of orientation, 30% GWAR, Lund.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Optimum glazing type (lowest annual energy use)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South</td>
<td>High solar transmittance (or SHGC) (types F to H)</td>
</tr>
<tr>
<td>North</td>
<td></td>
</tr>
<tr>
<td>East</td>
<td>Average solar transmittance (or SHGC) (types C to F)</td>
</tr>
<tr>
<td>West</td>
<td></td>
</tr>
</tbody>
</table>

5.1.2.2 Effect of orientation

Results indicate that the orientation had the largest effect on energy use with high solar transmittance glazing H. For glazing A, the effect of orientation on annual energy use was negligible. A change in orientation affected heating loads by at most 23%, cooling loads by at most 58% and annual energy use by at most 12% (with glazing H). The smallest effect of a change in orientation was 6% for heating, 41% for cooling and 12% for annual energy use (Table 5.3). Note that even with glazing A, the cooling load was significantly affected by a change in orientation (41%).

Table 5.3 Impact of a change in orientation on energy use, 30% GWAR, Lund.

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>Impact of a change in orientation on energy use</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Negligible</td>
</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Large</td>
</tr>
</tbody>
</table>

6-23% heating
41-58% cooling
5-12% annual
Thus, while the impact on the heating demand and on annual energy use due to a change in orientation was about the same as the impact of changing the glazing type (see previous section), the glazing type had a much larger impact (about twice as large) on cooling loads than the orientation (for 30% GWAR, in Lund).

An important finding is that the cooling demand was fairly constant from east to west (going through south) while the heating demand varied substantially from east to south and from south to west. Thus, while rotating the building 90° from east to south or from west to south reduced heating loads dramatically, cooling remained approximately the same. This explains why average solar transmittance glazing yields lower annual energy use on east and west facades while high solar transmittance glazing performs better in terms of annual energy use on the south facade as discussed in the previous section (see Table 5.2).

5.1.2.3 Effect of glazing-to-wall area ratio

In Lund, an increase in GWAR generally resulted in an increase in cooling and a reduction in heating loads. The impact of the GWAR on cooling loads was similar for east (thus west) and south orientations while the reduction in heating loads due to an increase in GWAR was significantly greater on the south than on the east (thus west) facade. Generally, the impact of a change in GWAR on energy use was thus the most significant on the south facade (Table 5.4). On the north facade, the increase in cooling was approximately equal to the reduction in heating for a given GWAR. However, the impact of a change in GWAR was generally moderate for this orientation. Overall a change in GWAR affected heating by 0-48%, cooling by 57-98% and annual energy use by 0-18% (Table 5.4).

Table 5.4  Impact of a change in GWAR on energy use, Lund.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Impact of a change in GWAR on energy use</th>
</tr>
</thead>
<tbody>
<tr>
<td>South</td>
<td>very large 0-48% heating</td>
</tr>
<tr>
<td>East</td>
<td>large 57-98% cooling</td>
</tr>
<tr>
<td>North</td>
<td>moderate 0-17% annual</td>
</tr>
</tbody>
</table>
Results indicate that, in Lund, a smaller GWAR yields a lower annual energy use on the east (thus west) facades than on the south and north facades. When heating and cooling loads were added in a 1:1 ratio, annual energy use was minimal at solar apertures (product of the SC and GWAR) around 0.2 on the south facade, around 0.12 on the east facade, and between 0.2-0.3 on the north facade (Table 5.5). Thus, in Lund, the optimum GWAR for south-orientated office rooms was about 22% for clear glass, 30% for low-e coated glass (SC=0.63), over 40% for average transmittance reflective and absorbing glass (SC=0.44-0.48), etc. For east-orientated (and west-orientated) rooms, the optimum GWAR was 14% for clear glass, 19% for the low-e coated glass, slightly over 25% for average transmittance glazing (SC=0.44-0.48), etc. On the north facade, the optimum GWAR was 23-34% for clear glass, 32-48% for low-e coated glass (SC=0.63), 42-68% for average transmittance solar-protective glazing (SC=0.44-0.48), etc. The results thus also indicate that solar-protective glazing should only be used with large glazing areas (> 40%) on north and south facades but can be energy-efficient with GWAR around 25% on east (and west) facades. Generally, however, the energy use of north-orientated rooms was negligibly affected by the GWAR. Remember that these conclusions are based on simulations with constant thermal losses under steady state conditions without solar radiation.

Table 5.5 Optimum solar aperture as a function of orientation, Lund.

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Optimum solar aperture (SA) (lowest annual energy use)</th>
<th>GWAR and glazing types corresponding to the SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>South</td>
<td>0.2</td>
<td>22% - type H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30% - type F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 40% - types C, D</td>
</tr>
<tr>
<td>East</td>
<td>0.12</td>
<td>14% - type H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19% - type F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25% - types C, D</td>
</tr>
<tr>
<td>North</td>
<td>0.2-0.3</td>
<td>23-34% - type H</td>
</tr>
<tr>
<td></td>
<td></td>
<td>32-48% - type F</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42-68% - types C, D</td>
</tr>
</tbody>
</table>

5.1.2.4 Effect of climate
The highest annual energy demand was in Luleå. Montreal was second. Stockholm and Oslo were third with remarkably similar annual energy trends. Lund had the lowest annual energy use of all cities tested (Table
5.6). The cooling demand was generally higher in Montreal and heating loads were also important in this Canadian city. Surprisingly, the annual cooling demand was similar for all the Swedish cities tested.

Results also show that an optimum glazing strategy is climate-dependent. In general, energy use was affected more by the glazing strategy and orientation in Montreal than in the other cities because Montreal receives much more global (and direct) solar radiation. Thus, orientation and glazing type are key issues in Montreal. The smallest relative impact of glazing type and orientation on annual energy use was in Luleå (Table 5.6).

Table 5.6 Annual energy use and impact of orientation and glazing type on energy use.

<table>
<thead>
<tr>
<th>City</th>
<th>Annual energy use</th>
<th>Impact of a change in orientation or glazing type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luleå</td>
<td>high</td>
<td>small</td>
</tr>
<tr>
<td>Montreal</td>
<td></td>
<td>large</td>
</tr>
<tr>
<td>Stockholm - Oslo</td>
<td></td>
<td>moderate</td>
</tr>
<tr>
<td>Lund</td>
<td>low</td>
<td>moderate</td>
</tr>
</tbody>
</table>

Results also show that a change in climate affected heating loads by 44-48% for 20% GWAR and by 45-57% for 50% GWAR. Cooling was affected by 50-80% for 20% GWAR and by 28-42% for 50% GWAR. Annual energy use was affected by 43-46% for 20% GWAR and 40-44% for 50% GWAR by a change in climate (Table 5.7). Note, however, that for the 50% GWAR, only 2 glazing types were studied, owing to the method. This explains why the effect of a change in climate on cooling loads was much smaller than for 20% GWAR. (The glazing type is a factor which has a significant effect on the cooling demand).

Table 5.7 Impact of a change in climate on energy use.

<table>
<thead>
<tr>
<th>GWAR</th>
<th>Impact of a change in climate on energy use</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>44-48% heating 50-80% cooling 43-46% annual</td>
</tr>
<tr>
<td>50%</td>
<td>45-57% heating 28-42% cooling 40-44% annual</td>
</tr>
</tbody>
</table>
The study also shows that for heating loads and annual energy use, the impact of a change in glazing type was about the same as the impact of a change in orientation. As shown before, however, the glazing type had more effect than the orientation on cooling loads. Note also, that glazing type and orientation influenced heating much more in Montreal than in Luleå but cooling was influenced more by a change in glazing or orientation in Luleå than in Montreal. This is due to the fact that Montreal receives more solar radiation than Luleå during the winter and less solar radiation than the Swedish town during the summer.

In colder cities like Montreal and Luleå, increasing the GWAR (from 20 to 50%) resulted in reductions in annual energy use, especially on the south facade (13% in Montreal and 1% in Luleå with glazing F). In Lund, Stockholm and Oslo, an increase in GWAR (from 20 to 50%) resulted in an increase in annual energy use on the east facade since large glazing areas yielded large cooling loads. Average transmittance glazing performed better with 50% GWAR in Lund, Stockholm and Oslo. For Montreal and Luleå, average and high transmittance glazings performed approximately in the same way.

5.1.2.5 Relative effect of glazing type, orientation, GWAR and climate

In conclusion, it should be noted that the heating demand and annual energy use seemed to be primarily affected by the climate. The glazing area (GWAR) was a secondary factor affecting heating and annual energy use while the glazing type and orientation were the factors having the smallest relative impact on the heating demand and the annual energy use (Table 5.8). Note, however, that for the last 3 parameters (GWAR, glazing type and orientation), the figures presented in Table 5.8 are limited to Lund and that the figure presented for the climate takes into account all glazing types and orientations studied.

<table>
<thead>
<tr>
<th>Heating</th>
<th>Cooling</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate (44-57%)</td>
<td>Glazing area (57-98%)</td>
<td>Climate (40-46%)</td>
</tr>
<tr>
<td>Glazing area (0-48%)</td>
<td>Climate (28-80%)</td>
<td>Glazing area (0-18%)</td>
</tr>
<tr>
<td>Glazing type (11-27%)</td>
<td>Orientation (41-58%)</td>
<td>Orientation (5-12%)</td>
</tr>
<tr>
<td>Orientation (6-23%)</td>
<td>Glazing type (4-10%)</td>
<td></td>
</tr>
</tbody>
</table>
The figures for cooling are somewhat different. Cooling seems to be primarily affected by factors purely connected with fenestration design i.e. the type and size (GWAR) of glazing. The climate seems to have a smaller effect on cooling compared with the effect of the glazing type and area. Finally, the orientation was the factor with the least effect on cooling loads. Again, one should be careful in interpreting those results since the analysis of the impact of orientation, glazing type and GWAR was limited to Lund. It might be different in other climates.

5.1.3 Conclusions from the peak loads analysis

The analysis of peak loads for Lund and Montreal with 30% GWAR orientated south showed that peaks occurred approximately at the same time during the day, regardless of the glazing type and city. The heating peak load occurred around 07.00 hours while the cooling peak load was between 13.00-16.00 hours for cooling. In general, heating peaks tended to occur earlier in the morning during the spring and autumn while cooling peaks occurred later in the afternoon during the spring and autumn.

The analysis also showed that annual heating peak loads were approximately twice as large in Montreal as in Lund. The glazing solar transmittance did not significantly affect the magnitude of the annual heating peak in either Montreal or Lund. This is easily explained by the fact that there is almost no solar radiation at the time when the heating peak load occurs (07.00 hours).

In contrast, the magnitude of the annual cooling peak loads increased as a function of the glazing solar transmittance. In Lund, reducing the glazing solar transmittance reduced peaks by as much as 61%, while the figure was only 32% for Montreal. Also, for high solar transmittance glazing (type H), annual peaks were of the same magnitude in Lund and Montreal while the annual peak cooling load was about twice as large in Montreal as in Lund with low solar transmittance glazing (type A). Results thus indicate that peak cooling loads (and thus, equipment sizing) are influenced more by the glazing type in Lund than in Montreal. Montreal has higher outdoor temperatures in the summer meaning that the temperature may be the dominant factor that determines peak loads.

This analysis generally showed that while annual energy use is more strongly affected by the glazing type and orientation in Montreal than in Lund, the peak cooling loads are affected more by the glazing type in Lund than in Montreal.
5.1.4 Conclusions from the indoor temperature analysis

A brief analysis of indoor temperatures, in Lund and Montreal, for glazings with 30% GWAR orientated towards the south showed that higher indoor temperatures were reached in Montreal when no cooling system was used. The analysis also showed that glazing A can eliminate the need for a cooling system in Lund while in Montreal, even glazing A yielded a large number of hours (306 “working” hours or 2 “working” months) with indoor temperatures above 28°C. The use of very low solar transmittance glazing (type A) can thus be justified in Lund, in buildings without a cooling system. Other options, such as seasonal shades should, however, be considered.

The analysis showed that cooling was mandatory in Montreal, for all glazing types with a GWAR of 30% orientated to the south. In this city, changing the glazing transmittance reduced the number of hours with indoor temperature above 28°C by at most 50%.

5.2 Limitations

5.2.1 Simulation method

Results and conclusions drawn from this research were reached through simulations of the energy performance of one single office room. Results were not compared with experimental data or else and should be considered in the light of the assumptions involved in any type of simulations.

Also, some limitations are attributable to the simulation method itself and the programs used. As mentioned in the Method section, DEROB-LTH calculates the solar position for only the middle day of the month. This may have resulted in an over- or under estimation of the solar heat gain in some cases. Another major limitation is connected with the angular dependency of coated glazing. As mentioned in the Method section, the optical properties were calculated using WINDOW 4.1. This program gives accurate angular dependent properties for homogeneous glass. For coated glazing, however, the program assumes the same angular properties as typical 3-mm clear glass for solar transmittance greater than 65% and the angular properties of 3-mm bronze glass for solar transmittance lower than 65%. This assumption means that for high angles of incidence, the solar heat gain factor may have been over- or under estimated.
Finally, it should be remembered that the analysis of indoor temperatures was based on one single figure calculated for a central point in the room. This single data is, by no means, an indication of thermal comfort in the room. Other limitations attributable to the simulation programs used are mentioned in the Method section.

5.2.2 Shoe box

Office buildings usually include both peripheral and interior zone spaces. According to ASHRAE (1996) peripheral zones have variable loads because of changing sun position and weather. These zones typically require heating in the winter as shown in the present study. Also, during intermediate seasons, one side of the building may require cooling, while another side requires heating. However, the interior zone spaces usually require a fairly uniform cooling rate throughout the year, according to ASHRAE (1996), because their thermal loads are derived almost entirely from lights, office equipment and people. Interior office zones also usually have a higher density of people (and equipment).

In this study, the energy performance of only one peripheral office room of one standard rectangular size was studied. It would be erroneous to extend the energy trends derived here to one entire building with interior and peripheral zones. The interior zones do not receive solar radiation and, thus, the energy balance of these zones may differ substantially from that of peripheral zones. The results of this study should be considered in view of this major limitation.

5.2.3 Energy systems

As mentioned in the Method section (3.3.1.1), it was assumed, from the beginning of the study, that the same amount of energy was used for producing 1kWh of heat or 1kWh of cooling in the building. This situation rarely occurs in a real building. In a real context, cooling saving options may be preferred to heating saving options because the COP of the heating system is higher (better) than that of the cooling system. The results of the study should thus be interpreted bearing this limitation in mind.

The economical aspect was also left out of the study although energy costs may be a decisive factor in many practical cases. For example, cooling saving options may be preferred to heating saving options because the energy source used for cooling (for example electricity) is more ex-
pensive than the energy source for heating (for example oil). The relative costs of equipment for cooling and heating and equipment sizing aspects can also influence the choice of glazing.

Results of this study should thus be viewed as a framework of energy totals that need to be adjusted to the appropriate performance, economical or even, environmental index before different glazing options are recommended.

5.2.4 Other limitations

This study clearly focused on energy use for heating and cooling an office room. In commercial buildings, however, a large part of the energy load is attributable to lighting and equipment. These end-uses were assumed to have constant energy consumption throughout this study. A new trend in offices is to use dimmable lights responding to either occupant use or daylighting availability. Such a system can save electricity use for both lighting and cooling since the heat from lights is removed when acceptable daylighting levels are reached in the room. In order to model this kind of system, however, advanced daylighting and lighting simulations must be used in conjunction with thermal simulations. Some energy simulation programs (for example, DOE and ESP) also offer the possibility to model daylighting and energy use for cooling and heating in an integrated way. This was outside the scope of the present study but will be the subject of future studies by the author.

5.3 Future work

Issues of thermal comfort and energy use in daylit buildings (with dimmable lighting systems) equipped with solar-protective glazing should be investigated further. Much work remains in these areas, especially for buildings located in cold climates.

Some work also remains to develop more accurate algorithms for the angular dependency of the optical properties of coated and tinted glazings. Progress in this area is encouraging and results of the present study will hopefully be reviewed in a near future with a more accurate simulation tool or data in hand.

Results of the present study have generally shown that solar-protective glazing can reduce cooling but increase heating loads significantly, resulting ultimately in higher annual energy use in heating-dominated climates. Thus, it appears that while there are benefits in using solar-protective
glazing during the summer, there are also major drawbacks to reducing solar gains in a building throughout the winter. Dynamic solutions should, in theory, be much more energy-efficient, in cold and temperate climates. Thus, energy use patterns with seasonal or dynamic shades and smart (or switchable) glazing should be investigated and the resulting energy savings should be compared with the ones obtained in the present study. Simple systems such as seasonal exterior shades combined with clear glazing have already proved to be excellent solutions for cold climates in comparison with solar-protective glazing (see Dubois, 1998). Much work remains in this area to estimate the impact of shading devices and dynamic glazing systems on energy use, thermal and visual comfort and daylighting utilisation.
6 Summary

Annual energy use for heating and cooling a standard, rectangular office room equipped with various types of solar-protective glazings was studied with the aim of identifying the glazing optical properties that yield low energy use in cold climates. The office room was alternately equipped with reflective, heat-absorbing (tinted), low-emissivity and clear glazing with shading coefficients varying between 0.16-0.86. The orientation was varied by 45° increments and glazing-to-wall area ratios (GWAR) of 0-, 10-, 20-, 30-, 50-, and 70% were tested in various climates: Lund, Stockholm and Luleå (Sweden), Oslo (Norway) and Montreal (Canada). Peak loads and indoor temperatures in the centre of the room were also studied for Lund and Montreal, with 30% GWAR and the south orientation.

The study was carried out through computer simulations with the program DEROB-LTH, recently supplemented with an improved angular-dependent algorithm for windows. The program WINDOW-4.1 was also used to calculate the angular-dependent optical and thermal properties of the glazings on the basis of manufacturers’ data for normal incidence. The room’s geometry, thermal losses, internal loads, ventilation and infiltration rates and heating and cooling temperature set points were kept constant throughout the study. Thermal losses were controlled by varying the insulation thickness in the opaque wall around the window as a function of each window’s U-value. This method allowed the inclusion of windows with a wide range of U-values in the study.

An analysis of hourly load fluctuations showed that heating peak loads occurred during the weekends when only one heating temperature schedule was used for all days of the week. The study thus suggests that a different heating schedule should be used for weekends and that simulation programs should allow the modelling of a flexible heating temperature schedule. Otherwise, weekend loads determine the size of the heating equipment. It was estimated that allowing temperatures to drop to 18°C during the weekends could save about 4% of the annual energy demand.

The study generally showed that solar-protective glazings reduce cooling loads significantly but yield higher heating loads thus resulting in a higher annual energy demand in most cases. Results also indicated that
the impact of a change in glazing transmittance and orientation on heating loads (and annual energy use) was of the same magnitude while the glazing type affected cooling loads more significantly (about twice as much) than the orientation. Another important finding was that the low-emissivity coated glazing ($SC = 0.68$) appeared to be an energy-efficient solution for all orientations and climates while extremely low solar transmittance bronze reflective glazing ($SC=0.16$) was always a poor solution.

An analysis of annual energy use for heating and cooling showed that the optimum glazing choice was orientation-dependent. Generally, the glazing type had the most significant impact on annual energy use on the south facade. Also, with 30% $GWAR$, north and south orientated rooms had lower annual energy use with high solar transmittance glazing like clear and low-e coated glass ($SC > 0.6$) while on east and west facades, average transmittance glazing ($0.4 < SC < 0.6$) performed better. On the south facade, there is a larger potential for passive solar utilisation in the winter. Thus, increases in cooling resulting from high transmittance glazing were easily offset by large reductions in heating. On east and west facades, the increases in cooling resulting from high transmittance glazing were not offset by the reductions in heating. On the north facade, the small increases in cooling due to high transmittance glazing were easily offset by small reductions in heating loads. This facade receives practically no direct solar radiation in the winter indicating that the reductions in heating loads were mostly generated by diffuse solar radiation.

The results also indicated that larger glazing areas performed better for south and north orientated rooms than for east (and west) orientations because of a larger potential for solar utilisation in the winter on the south facade and relatively low cooling demand on the north facade. When heating and cooling loads were added in a 1:1 ratio in Lund, the annual energy use was minimal at solar apertures (product of the $SC$ and $GWAR$) around 0.2 on the south facade, around 0.12 on the east facade, and between 0.2-0.3 on the north facade. Thus, the optimum $GWAR$ for south-orientated office rooms was 22% for clear glass, 30% for low-e coated glass ($SC=0.68$) and over 40% for average transmittance reflective and absorbing glass ($SC=0.44-0.48$), etc. For east-orientated (and west-orientated) rooms, the optimum $GWAR$ was 14% for clear glass, 19% for the low-e coated glazing and around 25% for average transmittance glazing. On the north facade, the optimum $GWAR$ was 23-34% for clear glass, 32-48% for low-e coated glass and 42-68% for average transmittance solar-protective glazing. Thus, the study also indicated that average transmittance solar-protective glazing should only be used with large $GWAR (> 40\%)$ on south and north facades but can be energy-efficient with $GWAR$ around 25% on east (and west) facades.
A comparison of energy use between 5 cold climate cities indicated that Luleå had the highest annual energy use. Montreal was second mainly due to high cooling loads. Stockholm and Oslo came third with very similar energy trends and Lund had the lowest annual energy use. Results indicated that the optimum glazing strategy is also climate-dependent. In general, Montreal’s annual energy use was affected more by a change in glazing or orientation than all other cities because this city receives more insolation throughout the year. The smallest relative impact of orientation and glazing type on annual energy use was in Luleå. In colder cities like Montreal and Luleå, an increase in GWAR (from 20 to 50%) resulted in reductions in annual energy use, especially on the south facade. In Lund, Stockholm and Oslo, increasing the GWAR generally yielded higher annual energy use, especially on the east facade since large glazing areas generated large cooling loads hardly offset by reductions in heating. With 50% GWAR, average to high transmittance glazing performed approximately in the same way in Montreal and Luleå while average transmittance glazing generally performed better in Lund, Stockholm and Oslo. The study thus suggests that higher transmittance glazing or larger GWAR should be used in sunny, cold cities like Montreal and Luleå where there is some potential for solar utilisation in the winter and/or where heating loads are substantial.

An analysis of peak loads for south-orientated rooms and 30% GWAR showed that peaks occurred around the same time regardless of the orientation, glazing type and climate for all cases but one (east orientation, clear glass). Heating peaks occurred around 07.00 hours in the morning while peak cooling loads were in the afternoon between 13.00-16.00 hours, both in Lund and Montreal. In contrast, the lowest heating load was in the afternoon while the lowest cooling load was around 07.00 hours in the morning. Annual heating peaks were about twice as large in Montreal as in Lund but the peaks were not affected by the glazing transmittance. This is easily explained by the fact that there is little solar radiation incident on the building at 07.00 hours. In contrast, the cooling peak was dependent on the glazing transmittance, especially in Lund where a change in glazing type reduced peak loads by up to 61%. The impact of glazing type on the peak cooling was smaller in Montreal (at most 32%).

A brief analysis of indoor temperatures at the centre of the room for south orientation and 30% GWAR indicated that the low solar-transmittance reflective glazing (SC=0.16) eliminated the need for a cooling system in Lund. In Montreal, however, even with extremely low transmittance glazing, much of the summer “working” time (2 months) had temperatures well above the comfort zone limit (> 28°C).
The study thus generally indicates that solar-protective glazing can be energy-efficient in cold climates provided that an appropriate glazing area is selected and that the orientation and climate are taken into consideration during the design. For example, in Lund, average transmittance solar-protective glazing ($0.4 < SC < 0.6$) was energy-efficient, with large $GWAR (> 40\%)$ on south and north facades or with smaller $GWAR (25\%)$ on east and west facades. Very low solar transmittance glazing should, however, be avoided except for offices that do not have artificial cooling. However, the study showed that a reduction in beneficial solar gains in the winter always resulted in a higher heating demand. Since the heating demand was many times larger than the cooling demand for all cities included in the study, the use of solar-protective glazing often resulted in higher annual energy use. This study thus suggests that more flexible solutions such as seasonal or dynamic shading or switchable (smart) glazing should be researched as they offer the potential to reduce solar gains when they are a nuisance while allowing a passive utilisation of solar radiation during the winter. Even a small amount of diffuse radiation on the north facade reduced heating loads. It should also be remembered that the potential for reducing overall energy use may be much greater with clear glazing in buildings where artificial lighting is dimmed as a function of daylighting. This latter possibility, along with shading, needs further investigation. Thermal and visual comfort should also be studied more thoroughly.
References


References


Solar-Protective Glazing for Cold Climates


Solar-Protective Glazing for Cold Climates


Appendix A

Calculations for constant thermal losses

1) Determination of an overall U-value for the exterior wall

In this research, the impacts of thermal exchanges (U-value) on energy use were eliminated in order to isolate the energy effects of interest i.e. the impact of glazing optical properties on energy use. Thus, thermal exchanges for the whole office room were approximately equivalent amongst all cases studied. Since a range of window areas and window U-values were used, the thermal transmittance in the opaque wall surrounding the window was adjusted to yield constant thermal losses (or gains) through the glazing-frame-wall system. This was achieved by adjusting the insulation thickness in the opaque wall surrounding the window.

The insulation thickness in each wall depends on the overall thermal transmittance (U-value) defined for the glazing-frame-wall system. This overall thermal transmittance is an arbitrary value that influences the number of cases that can be studied. If this value is too low, cases with large glazing areas or high glazing U-values must be eliminated from the study. If this value is too high, small windows will result in too thin insulation layers in the walls.

One way to determine the overall U-value of the glazing-frame-wall system is to use the requirements for building envelope prescribed in building codes. The Swedish code (Boverket, 1997) demands an overall thermal transmittance for the whole building. Since the design of the whole building is not defined in this study, it is impractical to use the Swedish provisions as a basis to determine the exterior wall’s thermal transmittance. The Canadian code (NRC, 1997), on the other hand, has a prescriptive route giving thermal transmittance values for each separate building component. For Montreal (Quebec, region A), the following requirements apply:

- Above ground building assemblies, walls: 0.33 W/m²°C
Supposing a 30% GWAR (with 0.1-m frame around each window), the following areas for glazing, frame and wall are obtained:

\[ A_{\text{glazing}} = 2.35 \text{ m}^2 \]
\[ A_{\text{frame}} = 0.95 \text{ m}^2 \]
\[ A_{\text{wall}} = 4.53 \text{ m}^2 \]

The requirement for fenestration\(^{11}\) is (fenestration-to-wall ratio = 0.4 - 0.5):

- Fenestration, fixed glazing without sash: 1.90 W/m\(^2\)°C

The glazing-frame-wall system thermal transmittance can be calculated using (Boverket, 1997, p. 116; and NRC, 1997, section 3.4.2, p. 22):

\[
U_m = \sum_{i=1}^{n} \frac{U_i A_i}{A_{om}}
\]  \hspace{1cm} (A.1)

where

- \(U_m\) = maximum permissible average thermal transmittance (W/m\(^2\)°C)
- \(U_i\) = thermal transmittance of each building component (W/m\(^2\)°C)
- \(A_i\) = area of the surface, in contact with the heated indoor air, of each building component (m\(^2\))
- \(A_{om}\) = aggregate area of the surfaces, in contact with the heated indoor air, of enclosing element of structure (m\(^2\)).

Thus,

\[
U_m = \frac{U_{\text{wall}} A_{\text{wall}} + U_{\text{window}} A_{\text{window}}}{A_{om}} = \frac{(0.33)(4.53) + (3.30)(1.90)}{(7.83)} = 0.99 \text{ W/m}^2\text{°C}
\]

2) Calculation of the opaque wall U-value

Using an overall U-value of 0.99 W/m\(^2\)°C for the glazing-frame-wall system, the U-value for the opaque wall can be calculated using equation A.1. Taking the triple-pane, clear glazing case (U-value = 1.88 W/m\(^2\)°C) surrounded by the 0.1-m wood frame (U-value = 2.16 W/m\(^2\)°C), we have:

---

\(^{11}\) In the Canadian code, requirements are prescribed for the window as a whole. There are no separate provisions for frame and glazing.
Using the same equation, the wall U-value can be calculated for every combination of glazing type and area included in the study. Results of this operation are shown in Table A.1 below:

Table A.1 Opaque wall U-value for a glazing-frame-wall system U-value = 0.99 W/m²°C.

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>U-value (W/m²°C)</th>
<th>Glazing-to-wall area ratio (GWAR) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>A</td>
<td>2.06</td>
<td>0.79</td>
</tr>
<tr>
<td>B</td>
<td>2.62</td>
<td>0.73</td>
</tr>
<tr>
<td>C</td>
<td>1.87</td>
<td>0.82</td>
</tr>
<tr>
<td>D</td>
<td>1.87</td>
<td>0.82</td>
</tr>
<tr>
<td>E</td>
<td>2.63</td>
<td>0.73</td>
</tr>
<tr>
<td>F</td>
<td>1.00</td>
<td>0.93</td>
</tr>
<tr>
<td>G</td>
<td>1.88</td>
<td>0.81</td>
</tr>
<tr>
<td>H</td>
<td>2.65</td>
<td>0.72</td>
</tr>
</tbody>
</table>

Table A.1 shows that out of 41 cases, 18 must be eliminated because a negative U-value is obtained for the wall. In these cases, the losses through the glazing are greater than 0.99 W/m²°C. Thus, the thermal exchanges in the wall must be negative or "inverse" to compensate for the large losses occurring through the glazing.

Since more than 40% of the cases must be eliminated from the study with an overall U-value of 0.99 W/m²°C, this value was increased to allow the study of a larger number of cases. A small sensitivity analysis was made to determine an optimal overall U-value.
3) Sensitivity analysis: glazing-frame-wall system U-value

The glazing-frame-wall system overall U-value was modified by 0.3 W/m²°C increments between 0.9 and 1.8 W/m²°C and the number of cases that could be included in the study were computed. Cases that yielded negative U-values for the opaque wall were eliminated. Results of this small sensitivity analysis are presented in the table below.

Table A.2 Number of cases included as a function of glazing-frame-wall system U-value.

<table>
<thead>
<tr>
<th>Overall U-value (W/m²°C)</th>
<th>Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>23</td>
</tr>
<tr>
<td>1.2</td>
<td>30</td>
</tr>
<tr>
<td>1.5</td>
<td>31</td>
</tr>
<tr>
<td>1.8</td>
<td>34</td>
</tr>
</tbody>
</table>

Table A.2 shows that an overall U-value of 1.2 W/m²°C allows the study of 7 more cases. Increasing the U-value to 1.8 W/m²°C (twice the initial U-value) only permits to include 4 more cases. Thus, a U-value of 1.2 W/m²°C is a reasonable choice for the whole glazing-frame-wall system since it allows the inclusion of more than 70% of the cases (30/41) without increasing thermal losses in an unrealistic way.

4) Calculation of the insulation thickness in the wall

The insulation thickness in the opaque wall was calculated for each combination of glazing area and glazing U-value using the l- and k-methods described in Hamrin (1990), taking into consideration an overall U-value of 1.2 W/m²°C for the glazing-frame-wall system. The resultant insulation thickness for each case is presented in table A.3. The first value is the thickness of the hard insulation board and the second value is the thickness of the mineral wool plus wood studs assembly. Note that when the U-value was very low, a 50-mm hard insulation board (k = 0.033 W/m°C) was added to the assembly. 11 cases were eliminated (−) due to negative U-values.
Table A.3 Insulation thickness (mm) in the wall according to each glazing type and area.

<table>
<thead>
<tr>
<th>Glazing type</th>
<th>Glazing-to-wall area ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>A</td>
<td>0/27</td>
</tr>
<tr>
<td>B</td>
<td>0/30</td>
</tr>
<tr>
<td>C</td>
<td>0/25</td>
</tr>
<tr>
<td>D</td>
<td>0/25</td>
</tr>
<tr>
<td>E</td>
<td>0/30</td>
</tr>
<tr>
<td>F</td>
<td>0/20</td>
</tr>
<tr>
<td>G</td>
<td>0/25</td>
</tr>
<tr>
<td>H</td>
<td>0/31</td>
</tr>
</tbody>
</table>

Table A.3 shows that as losses through the window increase with increasing GWAR or increasing glazing U-value, the insulation thickness in the wall also increases to compensate for the losses through the glazing. For the low-e coated glazing, however, the insulation thickness decreases with increasing GWAR because the glazing U-value is lower than the one required for the whole glazing-frame-wall system. Thus, as the glazing area is increased, losses through the opaque wall must also increase to compensate for the “too small” losses through the glazing.

5) Verification of constant thermal losses: null tests

In order to make sure that the thermal losses through the glazing-frame-wall system were approximately equivalent amongst all the cases included in the study, short 3-days simulations with a “null” climate file were performed. The null climate file has a constant outdoor temperature (0°C) and no solar radiation. To simplify the analysis, the energy balance in the office room was simplified to include only the effects of thermal losses through the glazing-frame-wall system on heating energy use. Thus, there was no ventilation and infiltration, no internal loads and the indoor temperature was constant (20°C). Results of these simulations are shown in Figure A.1.
Figure A.1 shows that the hourly heating loads were similar. While the lowest load was 14.44 Wh/hm², the highest load was 14.79 Wh/hm² and the average was 14.63 Wh/hm². Thus, the deviation from the average was, at most, 1% and the maximal difference between loads was 0.35 Wh/hm² (i.e. 2% of the average load). The null-tests thus indicate that the thermal losses are fairly constant for all the cases included in this study. Small differences between cases can be neglected.

![Hourly heating load graph](image-url)
Appendix B

Properties of exterior surfaces

Annual heating and cooling loads for a windowless office room with different combinations of exterior surface absorptance and emittance values are presented in Table A.4, for 3 orientations. The results show that, although there are no windows, heating and cooling loads vary significantly from north to south with 55% absorptance and 90% emittance (column #1). While heating loads vary by at most 6%, cooling loads vary by 37%. The effect of solar radiation on the wall is thus negligible for heating but significant for cooling.

With 0% exterior wall surface absorptance (columns #2 and #3), there are no effects of solar radiation incident on the opaque wall. The loads are the same, regardless of the orientation.

We could have chosen to set exterior surface properties according to column #2. However, simulations with 0% absorptance and 0% emittance (column #3) showed that the heating and cooling loads yielded were closer to the loads for an ordinary brick wall (column #1). Thus, the exterior wall surface absorptance and emittance were set to 0% for the entire parametric study.

Note that the effect of this parameter on cooling and heating loads is exaggerated here since the wall area is the largest (no window) and the smallest insulation thickness (19 mm) amongst all the cases was used.
Table A.4  Annual heating and cooling loads (kWh/year) for a windowless office room, 19 mm mineral wool, for 3 orientations and different exterior surface absorptance and emittance values.

<table>
<thead>
<tr>
<th></th>
<th>Column #1</th>
<th>Column #2</th>
<th>Column #3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Emittance=90%</td>
<td>Absorptance=55%</td>
<td>Emittance=90%</td>
</tr>
<tr>
<td>Annual heating</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kWh/year)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>1418.4</td>
<td>1498.9</td>
<td>1370.0</td>
</tr>
<tr>
<td>East</td>
<td>1377.8</td>
<td>1498.9</td>
<td>1370.0</td>
</tr>
<tr>
<td>South</td>
<td>1338.2</td>
<td>1498.9</td>
<td>1370.0</td>
</tr>
<tr>
<td>Annual cooling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(kWh/year)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>22.0</td>
<td>5.2</td>
<td>11.0</td>
</tr>
<tr>
<td>East</td>
<td>33.1</td>
<td>5.2</td>
<td>11.0</td>
</tr>
<tr>
<td>South</td>
<td>35.1</td>
<td>5.2</td>
<td>11.0</td>
</tr>
</tbody>
</table>
## Appendix C

### Internal heat gains from lights

Table A.5 Internal heat gain from lights used in various studies.

<table>
<thead>
<tr>
<th>Internal heat gain from lights</th>
<th>Measured</th>
<th>Converted value for office room (12.2 m²)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>general+task lighting: 2.5 W/m²+10 W/m²</td>
<td>not spec.</td>
<td>153 W</td>
<td>Christoffersen (1995)</td>
</tr>
<tr>
<td>1.6 W/ft² (17.2 W/m²) for installed lighting</td>
<td>not spec.</td>
<td>210 W</td>
<td>Hunn et al. (1993)</td>
</tr>
<tr>
<td>1.8 W/ft² (19.38 W/m²)</td>
<td>not spec.</td>
<td>236 W</td>
<td>Rundquist (1991)</td>
</tr>
<tr>
<td>&gt; 12 W/m²</td>
<td>no</td>
<td>144 W</td>
<td>Bylund in Ödesjö (1996)</td>
</tr>
<tr>
<td>10 W/m²</td>
<td>no</td>
<td>122 W</td>
<td>Jagemar (1996)</td>
</tr>
<tr>
<td>8-34 W/m²</td>
<td>not spec.</td>
<td>98-415 W</td>
<td>Johnson et al. (1984)</td>
</tr>
<tr>
<td>16 W/m² minimum</td>
<td>not spec.</td>
<td>195 W minimum</td>
<td>Tham (1993)</td>
</tr>
<tr>
<td>18 W/m² average connected load</td>
<td>not spec.</td>
<td>220 W</td>
<td>Sweitzer (1993)</td>
</tr>
<tr>
<td>10 W/m²</td>
<td>yes</td>
<td>122 W</td>
<td>NUTEK (1994)</td>
</tr>
</tbody>
</table>


## Appendix D

### Comfort zones and ideal indoor temperatures

Table A.6  Comfort zone and ideal indoor air temperatures.

<table>
<thead>
<tr>
<th>Source (Olgyay &amp; Olgyay, 1963)</th>
<th>Country or region</th>
<th>Ideal temperature</th>
<th>Comfort zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vernon</td>
<td>England</td>
<td>18.9°C in summer 16.7°C in winter</td>
<td>13.2-23.1°C</td>
</tr>
<tr>
<td>Bedford (1950)</td>
<td>England</td>
<td>18.2°C in winter</td>
<td>13.2-23.1°C</td>
</tr>
<tr>
<td>Klima (1938)</td>
<td>England</td>
<td>20.8°C with 50% R.H.</td>
<td></td>
</tr>
<tr>
<td>Markham (1947)</td>
<td>England</td>
<td>15.6-24.4°C with 40-70% R.H. (noon)</td>
<td></td>
</tr>
<tr>
<td>Brooks (1950)</td>
<td>England</td>
<td>14.4-21.1°C</td>
<td></td>
</tr>
<tr>
<td>Brooks (1950)</td>
<td>United States</td>
<td>20.6-26.7°C</td>
<td></td>
</tr>
<tr>
<td>Brooks (1950)</td>
<td>Tropics</td>
<td>23.3-29.4°C with 30-70% R.H.</td>
<td></td>
</tr>
<tr>
<td>Houghten &amp; Yaglou (1924)</td>
<td>United States</td>
<td>18.9°C (effective temperature)</td>
<td>17.2-21.7°C with 30-70% R.H.</td>
</tr>
<tr>
<td>Yaglou &amp; Drinker</td>
<td>not defined</td>
<td>21.7°C for men normally dressed in the summer and at rest</td>
<td>18.9-23.9°C for men normally dressed in the summer and at rest</td>
</tr>
<tr>
<td>Olgyay &amp; Olgyay (1963)</td>
<td>Temperate Zone of the United States</td>
<td>18.9-24.2°C in winter 20.0-27.8°C in summer with 30-65% R.H.</td>
<td>temperature never &gt; 29.4°C</td>
</tr>
</tbody>
</table>

12. The effective temperature is the temperature of an environment at 50% relative humidity that results in the same total heat loss from the skin as in the actual environment (ASHRAE, 1997). Two environments with the same effective temperature should evoke the same thermal response even though they have different temperatures and humidities (but they must have the same air velocities).
Appendix E

Effect of weekend temperature set points on annual energy use

The largest effect of temperature set points on annual energy use occurs for low solar transmittance glazing with a north orientation. Therefore, annual heating loads for glazing type A orientated north (30% GWA in Lund) are presented in Table A.7 for two heating temperature schedules. The first schedule (1) assumes 20°C during working hours (08.00-17.00) and 18°C the rest of the time. The second schedule (2) assumes 18°C all the time.

Table A.7 Heating loads for different heating temperature schedules.

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Heating load (kWh/m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) 18/20°C</td>
<td>All days of the year 115.3</td>
</tr>
<tr>
<td>(1) 18/20°C</td>
<td>Weekends 45.5</td>
</tr>
<tr>
<td>(2) 18°C all the time</td>
<td>Weekends 41.3</td>
</tr>
</tbody>
</table>

Table A.7 shows that energy use for heating during weekends represents 39% of annual heating energy use if the heating schedule for weekends is the same as for weekdays. Note that weekend days constitute only 29% of the time (2/7). When the temperature is set to 18°C at all times during weekends, the heating loads drop by 4.2 kWh/m² annually, meaning that a lower temperature schedule for weekends results in energy savings of 4% annually in the worst situation i.e. with low solar transmittance glazing on the north facade. This amount of energy is small compared to annual energy use and can be ignored in this parametric analysis to avoid having to run two sets of simulations for each case. For the peak loads analysis, however, the peaks occurring during weekends are ignored since, in a real situation, it is assumed that different heating schedules are used for weekdays and weekends.
Solar-Protective Glazing for Cold Climates