Solar Shading for Low Energy Use and Daylight Quality in Offices

Simulations, Measurements and Design Tools

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Keywords

Shading devices, solar protection, energy use, daylighting, visual comfort, cooling, heating, solar-protective glass, computer simulations, measurements, design tools, awnings, venetian blinds, screens

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Foreword

This thesis includes the publications listed below:

Reports

[I] Dubois, M.-C. (2001). *Impact of Solar Shading Devices on Daylight Quality: Measurements in Experimental Office Rooms.* Report TABK--01/3061. Lund University, Dept. of Construction and Architecture, Div. of Energy and Building Design. Lund (Sweden).

[II] Dubois, M.-C. (2001). *Impact of Solar Shading Devices on Daylight Quality in Offices: Simulations with Radiance.* Report TABK--01/3062. Lund University, Dept. of Construction and Architecture, Div. of Energy and Building Design. Lund (Sweden).

[III] Dubois, M.-C. (1998). *Solar Protective Glazing for Cold Climates: A Parametric Study of Energy Use in Offices.* Report TABK--98/3053. Lund University, Dept. of Building Science. Lund (Sweden). 134 pages.

[IV] Dubois, M.-C. (1997). *Solar Shading and Building Energy Use: A Literature Review. Part I.* Report TABK--97/3049. Lund University, Dept. of Building Science. Lund (Sweden). 118 pages.

Articles

[I] Dubois, M.-C. (2000). A Method to Define Shading Devices Considering the Ideal Total Solar Energy Transmittance. *Proc. of the Eurosun 2000 Conference,* June 19-22, Copenhagen (Denmark). (proceedings on CD-rom).

[II] Dubois, M.-C. (2000). A Simple Chart to Design Shading Devices Considering the Window's Solar Angle Dependent Properties. *Proc. of the Eurosun 2000 Conference,* June 19-22, Copenhagen (Denmark). (proceedings on CD-rom).

[III] Dubois, M.-C. (1999). The Design of Seasonal Awnings for Low Cooling and Heating Loads in Offices. *Proc. of the 5th Symposium on Building Physics in the Nordic Countries,* August 24-26, Göteborg (Sweden). Vol. 2. Chalmers University of Technology, Göteborg. pp. 505-512.

[IV] Dubois, M.-C. (1998). Awnings and Solar-Protective Glazing for Efficient Energy Use in Cold Climates. *Proc. of the International Conference on Renewable Energy Technologies in Cold Climates '98,* May 4-6, Montreal (Canada). Solar Energy Society of Canada Inc. Ottawa. pp. 380-385.

[V] Wallentén P., Kvist H. & Dubois, M.-C. (2000). ParaSol-LTH: A User-friendly Computer Tool to Predict the Energy Performance of Shading Devices. *Proc. of the International Building Physics Conference*, September 18-21, Eindhoven (The Netherlands). pp. 331-338.

This report contains a short summary of each publication listed above and a general discussion and conclusions. The conference articles included in this thesis are presented in the Appendix.

"And now in houses with a south aspect, the sun rays penetrate into the porticoes in winter, but in summer the path of the sun is right over our heads and above the roof, so that there is shade, if then, this is the best arrangement, we should build the south side loftier to get the winter sun and the north side lower to keep out the cold winds"

Socrates in Xenophon (c.430 to c.354 BC). *Memorabilia.* III. VIII.9-IX.

1 Introduction

Solar shading is a concern that has preoccupied human minds for a long period of time, aptly captured in Socrates' citation. This concern has, however, never been so topical as it is at present as it pertains office buildings, since many countries are faced with the necessity to reduce their national energy consumption while the use of electrical appliances and computers is constantly increasing. The necessity to reduce energy use is further challenged by an international architectural trend that promotes the use of large glass facades. Large glass facades generate overheating problems by creating a greenhouse effect and, in most situations, contribute to an increase in the cooling demand. Large glass facades are furthermore liable to yield visual problems–direct and reflected glare that is already exacerbated by the increasing use of computers in the modern office.

Solar shading is thus a necessity in office buildings, especially in offices with large glazing areas. Shading must therefore be carefully incorporated and planned at an early stage in the design process. Notwithstanding, the designer must take both the energy use (heating, cooling and lighting) and the visual comfort aspect into consideration during the design.

This thesis contributes to research in the field through investigations of the impact of solar shading devices on energy use and on daylight quality in office buildings. It forms a part of a larger research project on solar shading devices (Solar Shading Project, see Wall & Bülow-Hübe, 2001), that was initiated at Lund University in 1997. The Solar Shading Project, which has involved eight researchers since its initiation, is still in progress at the time of completing this thesis.

The research work presented in this thesis was mainly carried out between September 1996 and September 2001. The work presented in this thesis consists of four main parts:

1. A literature review (state-of-the-art) of the research about solar shading devices (Dubois, 1997);
2. Parametric studies of energy use for cooling/heating an office room with shading devices or solar-protective (tinted, reflective) glazing (Dubois, 1999, 1998a, 1998b);
3. The development of tools to define shading devices at an early and intermediate design stage (Dubois, 2000a, 2000b; Wallentén, Kvist & Dubois, 2000);
4. Studies of the impact of shading devices on daylight quality in office rooms (Dubois, 2001a, 2001b).

The following sections summarise briefly the main findings of each part.

2 Literature review

At the beginning of the Solar Shading Project in 1997, it appeared necessary to review the literature about solar shading in order to get a clear understanding of the state-of-the-art knowledge in the field and orientate our research work towards the areas which had not been covered in the past. A part of this literature review was reported in Dubois (1997). This review revealed that research on solar shading had been mainly focused on three main issues:

1. the thermal and solar-optical properties of shading devices;
2. the impact of shading devices on energy use for cooling, heating and lighting buildings;
3. the calculation methods to predict the impact of shading devices on energy use.

2.1 Thermal and optical properties

Thermal properties

The literature review indicated that a large number of studies have been performed so far to determine the thermal properties (i.e. the impact on the window U-value) of many types of shading devices. These studies have shown that shading devices affect the heat losses through windows in a significant manner. For example, it was shown that venetian blinds, draperies and roller shades inside single-pane, clear glass windows, reduce heat losses by 25 to 40 % and that metallic coated shades may further reduce heat losses by 45 to 58 % depending on the material and mounting method used.

The results of these studies generally show that the thermal resistance of the window-shade assembly can be greatly improved if:

- the shading device traps an air layer next to the window (edges are sealed);
- airtight fabrics are used;
- the shading device is close to the window pane;
- low-emissivity and light-coloured backings are used;
- multiple layers are used and the distance between the layers is small.

The reductions reported in the literature review are quite impressive. However, most studies were carried out with ordinary, single-pane clear glass windows, which explains why the relative heat loss reduction appears so high. Few studies have been carried out with double-pane glazing and no studies with triple-pane or special (low-e) coated glazing have been reported in the literature review. The determination of the relative improvement in the window U-value for triple-pane assemblies and special (low-e) coated glazing has been identified as an area of future research.

Solar-optical properties

A few studies about the solar-optical properties of shading devices were reported but the review suggests that work about thermal properties has been more abundant. The review shows that prismatic panes, interior venetian blinds, net and light curtains, and exterior vegetal sunscreen have been studied and thus have a characterised solar transmittance. The review further indicates that it is generally acknowledged that exterior devices are more effective (by about 35 %) than interior devices since exterior devices block solar radiation before it comes into contact with the building and a large part of the radiation absorbed in the exterior device is reflected and convected to the outdoor air. Light-coloured shades are also more effective (by 20-40 %) than dark-coloured ones, according to the literature[1] .

The review thus suggests that much work remains to determine the solar transmittance (reflectance and absorptance) of many shading devices. Especially, much research is needed to obtain the total solar transmittance (i.e. including secondary heat transmission effects), and the solar angle-dependent values, since most studies only provided the solar transmittance for normal incidence.

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1. Measurements carried out within the Solar Shading Project at Lund University, later showed that this is not necessarily true. For example, light-coloured translucent fabric awnings were found to have a higher g value (higher total solar transmittance) than identical awnings made of a similar fabric in a dark blue colour (see Wall & Bülow-Hübe, 2001).

Tremendous progress has been made in this area since the literature review was achieved in 1997. The total solar transmittance (g value) of many exterior shading devices and devices between panes has been determined within the Solar Shading Project at Lund University. This was achieved through outdoor measurements in twin hot boxes exposed to the natural climate and, more recently, through measurements in a solar simulator (see Wallentén & Wall, 1999; Wall & Bülow-Hübe, 2001 and the website of the Solar Shading Project, 2001). Moreover, measurements to determine the g value of many interior shading devices are presently in progress at Lund University and a standard procedure for carrying out these measurements is being developed.

2.2 Impact on energy use

The literature review showed that there are abundant studies about the impact of shading devices on energy use, with the first work on the subject reported as early as 1940. Research in this area first focused on the impact of shading devices on the cooling loads. As expected, all the studies showed that shading reduces the cooling load of buildings (by 23-89 %), with the highest savings obtained with devices with a low shading coefficient (i.e. low solar transmittance).

As time developed, experts noticed that shading devices may have a negative impact on heating loads since they reduce the useful solar gains during the winter. It was shown by many studies that, in heating-dominated climates, the most energy efficient shading strategy consisted of using shading devices with a high shading coefficient (high solar transmittance) because they allow some passive solar utilisation during the winter. Note, however, that this is only true for fixed shading devices and that the optimal alternative in heating-dominated climates is to use movable shading devices (with a low shading coefficient), which can be removed when free solar heat gains are available and useful. Many studies also showed that shading devices which reduce the heat losses through the window provide substantial additional energy savings in heating-dominated climates.

Since the middle of the 1980s, consideration has also been given to the impact of shading devices on daylighting and on the energy use for artificial lighting. Many investigations have shown that energy use for lights is an important part of the total energy use, especially in office buildings. Artificial lighting also produces additional internal heat gains, which must be removed through mechanical ventilation and cooling.

Daylight utilisation (instead of using artificial lights) thus has two advantages: it reduces the direct consumption of electricity for lights and indirectly reduces the cooling demand through a reduction of the internal heat load from lights. All the studies reported but one showed that daylight utilisation may reduce the total energy use and that increasing the window-to-wall area ratio results in overall energy savings in buildings with daylight utilisation. The potential for overall energy saving seems to depend on the climate.

The literature review indicated that many studies of the impact of shading devices on energy use for cooling and heating, and even lighting, have been performed so far. However, most of these studies were carried out using computer simulations with relatively simple algorithms using shading coefficients for the normal incidence or steady-state calculations. Moreover, most studies have only considered fixed shading devices and few studies have taken into consideration the daylighting/lighting aspect. The review thus suggested that future research in the field should include movable shading devices and impacts on daylight utilisation while energy simulation programs should be further developed (to include e.g. solar-angle dependent effects, impact on diffuse radiation, secondary heat transmission effects) and validated experimentally.

2.3 Calculation methods

The literature review indicated that many computer programs have been developed so far to calculate the impact of a shading device on the shading pattern on the building or to determine the optimum shape of a shading device to shade the entire window area. These programs are mainly based on geometrical considerations and are not designed for the prediction or minimisation of energy use in buildings.

A few advanced algorithms that predict the impact of shading devices (venetian blinds, vertical planar shades, awnings) on solar gains have been reported. This review indicated that work remains in this area to:

- include solar-angle dependent effects for all types of shading devices;
- include the effect of the shading device on diffuse radiation;
- include secondary heat transmission effects;
- validate the computer models against experimental data;
- connect these advanced shading algorithms to whole building energy simulation programs.

The Solar Shading Project at Lund University allowed major progress in this area. Advanced algorithms for windows and shading devices of arbitrary shape have been developed in the course of this project and implemented in the dynamic , whole building energy simulation program *Derob-LTH* (see Källblad, 1998). These models have also been validated against experimental data (Wallentén & Wall, 1999; Wall & Bülow-Hübe, 2001). The work which remains to be done within this area is summarised by the following points:

- Develop programs that calculate the impact of shading devices on daylighting and allow the prediction of the impact of heating, cooling and lighting in an interactive way;
- Develop computer models allowing the modelling of movable shading devices;
- Validate these programs with more global experimental data (i.e. including energy use of a whole building).

Note that some work to include daylighting in the energy simulation program *Derob-LTH* has been initiated by Bülow-Hübe and Källblad (in Bülow-Hübe, 2001). This work needs to be further developed to allow modelling of movable shading devices and it must be validated against experimental data.

3 Impact of shading devices on energy use

Two studies about the impact of solar shading on energy use were carried out. The first study (Dubois, 1998a, 1998b) investigated the impact of solar-protective (reflecting, absorbing) glazing on energy use, peak loads and indoor temperatures in a standard office room while the second study (Dubois, 1999) examined the impact of a seasonal awning on energy use in a south-oriented office room located in Stockholm.

3.1 Impact of solar-protective glass on energy use

In this study (Dubois, 1998a, 1998b), the annual energy use for cooling and heating a standard, rectangular office room was studied for various types of solar-protective glazing assemblies, various orientations (N, NE, E, SE, S, SW, W, NW), glazing-to-wall area ratios (GWAR = 0, 10, 20, 30, 50, 70 %) and climates (Lund, Stockholm, Luleå, Oslo, Montreal). The aim of this study was to identify the glazing properties (solar transmittance) which resulted in a low annual energy use. The effect of the glazing U-value on thermal losses was thus artificially controlled by increasing or reducing the insulation thickness in the opaque wall surrounding the window. This permitted isolation of the energy effects of interest i.e. the impact of the glazing solar transmittance on energy use.

The glazing assemblies studied included :

A. a double-pane window with a bronze reflecting glass (g value = 0.14)
B. a double-pane window with a blue reflecting glass (g value = 0.27)
C. a triple-pane window with a silver reflecting glass (g value = 0.38)
D. a triple-pane window with a blue absorbing glass (g value = 0.41)
E. a double-pane window with a blue absorbing glass (g value = 0.48)
F. a triple-pane window with two low-emissivity coatings (g value = 0.58)
G. a triple-pane, clear glass window (g value = 0.65)
H. a double-pane, clear glass window (g-value = 0.74).

The study was carried out through computer simulations using the dynamic energy program *Derob-LTH* (Källblad, 1998; Kvist, 1997). The program *Window-4.1* (LBL, 1994) was also used to calculate the solar angle-dependent optical properties of the glazing and steady-state (manual) calculations were used to determine the insulation thickness around the window, which made it possible to maintain a constant U-value (thermal losses) for all the cases.

The study showed that the optimum glazing transmittance (*g* value) and glazing-to-wall area ratio (GWAR) were orientation- and climate-dependent. With a GWAR of 30 %, south and north oriented rooms had a lower annual energy use with clear and low-e coated glazing assemblies (F, G, H above). For east and west orientations, glazing assemblies with an average transmittance (C, D, E) yielded a lower annual energy use. Similarly, the study showed that larger glazing areas were preferable on south and north than on east and west facades[2] .

On the south facade, there is a larger potential for passive solar utilisation in the winter. Increases in the cooling demand due to increases in the glazing transmittance or area are easily offset by the large reductions in heating provided by useful solar heat gains during the winter. On the east and west facades, the increase in cooling due to higher glazing transmittance or larger glazing areas is not offset by reductions in the heating demand, since there is not enough solar radiation on these facades during the winter. On the north facade, glazing assemblies with high transmittance or larger glazing areas performed better because they produced a relatively small increase in cooling compared with the reduction in heating load provided in the winter by the diffuse sky radiation.

The study also showed that in cold sunny cities like Montreal and Luleå, glazing assemblies with a higher solar transmittance or larger glazing areas resulted in lower annual energy use compared with more temperate and cloudy cities like Lund, Stockholm and Oslo. This occurred because there is a larger potential for passive solar utilisation during the winter in cities with a cold and sunny winter. Note that this conclusion is, again, only valid if larger glazing areas are compensated for by an increase in the insulation of the opaque parts of the building envelope.

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[2] Note, however, that this is only true on condition that constant total heat losses among all the cases studied (small and large window areas) prevail. It is possible to achieve this in reality by increasing the insulation thickness in the wall surrounding the window, to compensate for the extra heat losses due to the increase in window area. This is what is normally done with a performance based building code, as e. g. the Swedish Building Code (Boverket, 1999).

This study generally showed that solar-protective glazing may be an energy-efficient solution only on the east and west facades, where the potential for passive solar utilisation in the winter is relatively low in comparison with the south facade. However, the annual energy use in this study was simply calculated as the sum of space loads for cooling and heating. No account was taken of the relative performance of heating and cooling systems or the costs of heating versus cooling. In a scenario where cooling is more expensive or less efficient than heating, we may find that it is more economical to use tinted or reflective glass on all facades.

Subsequently, it was shown that the potential for energy savings is much greater if a simple movable awning is used in combination with clear glazing as shown in Dubois (1998b). In this case, the cooling demand obtained is approximately the same as the one obtained with the low transmittance glazing (A) and the heating demand is the same as that obtained with clear glazing. This solution is thus optimum, no matter what weight is attributed to heating and cooling demands in the calculation of the total energy use. The real potential for energy savings may even be much higher than what is shown in Dubois (1998b) since the potential for daylight utilisation is greater with clear glazing than with solar-protective glazing.

3.2 Impact of an awning on energy use

Another parametric study (Dubois, 1999) was carried out to investigate the impact of a seasonal awning's colour, geometry (length, width, slope) and seasonal management strategy on energy use for heating and cooling the same office room. In this case, the office room had a glazing-to-wall area ratio (GWAR) of 30 %; it was oriented towards the south direction and located in Stockholm (Sweden). This study was also carried out through computer simulations using the program *Derob-LTH*. Only seasonal awnings were tested in this case.

This study showed that large energy savings (around 12 kWh/m^{2}yr) could be obtained by using a simple seasonal awning but that equivalent additional energy use (around 11 kWh/m^{2}yr) may result if the awning remained in the window year-round (fixed awning). This demonstrated the necessity to remove shading devices during the heating season. The study also showed that it is essential that the awning's length be sufficient so that the entire window area is shaded when the sun is facing the window. This parameter had a significant impact on cooling loads.

The study further showed that a variation of the awning's colour had a moderate effect on the cooling demand (± 2.5 kWh/m^2yr) and it was found that light-coloured fabrics resulted in higher cooling loads than dark-coloured ones. This is due to the fact that the light-coloured fabrics in the study had a higher transmittance (g value) and this property was dominant. Note that most of the time, light-coloured fabrics have a higher transmittance than dark-coloured ones and it is thus an oversimplification to say that shading devices should have light colours. In this case we showed that the awning with dark colours reduced cooling loads more dramatically.

The study also showed that the awning's width had a negligible impact on cooling loads, as long as the awning overlapped the window by at least 30 cm on each side. Negligible additional energy savings were obtained with wider awnings. This is due to the fact that the solar rays leaking on the sides of the awning are insignificant with respect to annual cooling loads since both the incident and transmitted radiation are dramatically reduced as the angle between the sun and the normal to the window increases. This study thus showed that it may not be necessary to produce very large awnings or awnings with sides. In fact the diffuse radiation leaking on the sides of the awning may provide beneficial diffuse daylighting during the day.

Finally, a variation of the awning's slope–keeping the shading pattern on the window constant–showed that this parameter had a negligible impact on energy use. The main effect observed in this study was probably due to a change in the shading of the diffuse sky (due to a change in the awning's size).

4 Design tools

While carrying out the parametric studies described in the previous sections, we realised that parametric studies were very time-consuming because so many variations had to be modelled and studied before the most energy-efficient solution was identified. For example, in the study about seasonal awnings (Dubois, 1999), 31 simulations had to be performed before the optimum solution was reached. This is unrealistic, especially if we consider that solar shading is only one aspect to consider in the design of a whole building.

The reason why so many simulations had to be made was that the information available at the beginning of the study was not detailed enough. Using traditional design tools, e.g. sunpath diagrams, provided information about solar angles and incident solar radiation but failed to provide detailed information about specific energy needs in the building and the transmitted solar radiation according to specific times. Based on this experience, simple design tools were devised and proposed.

The first design tool (Dubois, 2000b) is a simple chart which provides some information about the solar angle dependent transmittance of the window as a function of solar position (sunpath). The second tool (Dubois, 2000a) consists of a few mathematical formulas which allow determination of the ideal (optimum) g value of the shading device based on the information provided by a single energy simulation with the bare window. Finally, a third tool, which is a simplified interface to the program *Derob-LTH*, was developed (Wallentén, Kvist & Dubois, 2000).

4.1 Chart showing the solar angle-dependent properties of the window

Traditional design tools like sunpath diagrams and shading masks proposed by e.g. Olgyay & Olgyay (1957) and Mazria (1979) are useful to determine the period when the window receives solar radiation and the appropriate shading mask to prevent insolation during this period. However, one limitation of these tools is that they only consider the solar radiation *incident* on the window and fail to indicate the amount of radiation *transmitted* through the window. Since the intensity of both the incident and transmitted solar beam varies as a function of the incidence angle of the sun with respect to the window, it is obvious that information about the total transmitted radiation should be provided, even at an early design stage.

An overlay showing the relationship between the sunpath and the window angular properties (solar transmittance) was developed and presented in Dubois (2000b). Once superposed on a sunpath diagram, this overlay shows the solar time for which the window g value (total solar transmittance) is the highest and the corresponding solar radiation at that time. This allows identification of the critical insolation periods on the window.

A design example was presented and it was shown that the new overlay allows identification of the optimum shading solution more precisely than the traditional methods. The chart is thus useful at an early design stage to identify the optimum shading masks rapidly, which avoids many iterations in the computer simulations performed at a later design stage in the design process.

4.2 Ideal total solar transmittance

This second design method was devised after it was observed that the ideal (i.e. yielding the lowest energy use) g value (g_i) of a shading device is a function of the total solar heat gains for each hour and the cooling load for that hour in the room. If the cooling loads are larger than the total solar contribution (total solar gains), then all solar radiation should be eliminated to yield the lowest cooling load and g_i is thus 0 %. On the other hand, if the cooling load is smaller than the solar contribution, it means that a part of the solar gains are being used in the building to offset losses through the envelope. This occurs in the spring and autumn when the intensity of solar radiation is high and the outdoor temperature is low. In this case, g_i is that proportion of the total solar gains which is utilised in the building (see Dubois, 2000a). Finally, if there are no cooling loads or no solar gains, g_i is 100 % since no shading is required.

The ideal g value g_i thus varies constantly over the year and day and it can be calculated for each hour of the year using the hourly values of cooling load and solar gains obtained through a single energy simulation for a year, for the bare window case. Average g_i values can then be calculated from the hourly values by using weighted averages as shown in Dubois (2000a). This makes it possible to identify the monthly and annual g_i values which yield the lowest energy use in the building. In the case of simple shading devices like screens, these average g_i values indicate the optimum screen transmittance. For more complex shading devices like awnings, the average g_i values can be used to estimate the portion of the window which must be shaded during each month, and the geometry of the shading device providing this shading pattern can be deduced.

4.3 Computer program *ParaSol*

Advanced energy simulation programs like *Derob-LTH* allow a detailed analysis of energy use as a function of shading alternative. The advantage of such programs is that the complex energy interactions between the shading device and the window (e.g. secondary heat transmission effects), the shading of the diffuse radiation and the solar-angle dependent properties are taken into consideration in the calculation in a dynamic way (hour by hour). However, this type of computer program is far too specialised and complex for many groups of professionals involved in the design process and simpler design tools are needed.

A simple, user-friendly interface to *Derob-LTH* called *ParaSol* was thus developed within the Solar Shading Project at Lund University (see Wallentén, Kvist & Dubois, 2000). *ParaSol* is a *Windows 95/98/NT* program written in *Visual Basics*. The main advantage of this program over the original calculation engine (*Derob-LTH*) is that both the input and output are greatly simplified. The input is made through a series of dialog boxes where the size of the room to analyse, the window geometry and window type, the building materials, the type of shading device and geometry are defined in a simple way. Once the input dialog boxes have been filled, the input data is "sent" to *Derob-LTH* to perform either a "simple" or "detailed" calculation. The simple calculation returns the monthly average and minimum "g" or "t" (for primary transmittance) values while the detailed calculation returns energy totals in the form of monthly and annual cooling and heating demands and peaks loads with and without the shading device as well as diagrams showing the frequency of overheating temperatures, etc. *ParaSol* can be used at a more advanced design stage to verify the hypotheses made at an earlier design stage using simpler tools like the ones proposed in Dubois (2000a, 2000b).

5 Impact of shading devices on daylight quality

The impact of shading devices on daylight quality in offices was investigated through measurements in experimental office rooms (Dubois, 2001a) and through computer simulations using the advanced lighting simulation program *Radiance* (Dubois, 2001b).

5.1 Measurements in experimental office rooms

The impact of shading devices on daylight quality in offices was studied through measurements in two south-oriented, experimental rooms located in the Daylight Laboratory of the Danish Building and Urban Research Institute, in Hørsholm, Denmark. These rooms are 3.5 m-wide by 6.0 m-deep and have a 1.78 m-wide by 1.42 m-high window. The daylight quality was assessed by considering five performance indicators: the daylight factor, the work plane illuminance, the illuminance uniformity on the work plane, the absolute luminance in the field of view and the luminance ratios between the work plane (paper task), the walls and the VDT screen.

The shading systems studied included ten interior shading (roller) screens and one standard venetian blind with 25 mm-wide, curved, white aluminium slats placed on the interior side of the window. Among the interior screens studied, three were black, one was dark brown, two were brown, two were medium brown and two were white. The venetian blind was studied with the slats in the horizontal position and in a closed position where the view to the outside was totally blocked.

The measurements were carried out under perfectly sunny and overcast conditions. The sunny day measurements were performed three times a day (i.e. in the morning, noon and afternoon) between July 2-19, 2001 while the overcast measurements were carried out between the end of

July and the end of August 2001. The measurements were carried out simultaneously in two rooms. One room was totally empty while the other room was furnished as a typical office room. In each room, the work plane illuminance and the illuminance on lateral walls was recorded by lux meters, while the luminance of the walls and window-shade combination was measured using a calibrated CCD camera and two luminance meters.

The results of the measurements show that the shading devices studied can be divided into three distinct groups:

Group 1:	**Group 2:**	**Group 3:**
Black screens	Closed V. B. (white)	Horiz. V. B. (white)
Brown screens		White screens

Group 1 consists of all dark-coloured (black and brown) screens; Group 2 includes the closed venetian blind while Group 3 includes the white screens and the horizontal venetian blind. The devices of Group 1 produced unacceptably low work plane illuminance and vertical luminance values which resulted in unsuitable luminance ratios between the task, the walls and the VDT screen. However, these devices reduced the luminance of the window (sky) to acceptable levels i.e. below 500 cd/m^2, most of the time. The devices of Group 3 did not prevent high window luminance but resulted in higher levels of work plane illuminance and wall luminance, which makes them suitable for traditional paper tasks. They also yielded high wall luminance values which resulted in some unacceptable luminance ratios between the task, the walls and the VDT screen. In this case, the wall behind the VDT screen and the task (paper) was more than three times brighter than the VDT screen.

The closed venetian blind (Group 2) was the only device which scored well on all performance indicators considered. It provided ideal illuminance levels for a combination of paper and computer work, a high degree of illuminance uniformity, prevented extreme luminance values and resulted in favourable wall luminance levels compared with the luminance of a standard VDT screen. However, the view to the outside was totally blocked in this case.

The study showed that none of the shading screens studied met all the requirements of all the performance indicators considered. The dark-coloured screens met the requirement regarding the maximum luminance in the field of view but failed to meet the requirements regarding minimum work plane illuminance and wall luminance levels. This resulted in unacceptable luminance ratios between the VDT screen and the wall behind the screen and between the VDT screen and the task. On the other hand, the white screens did meet the requirements regarding minimum work plane illuminance and wall luminance levels. However, they often produced illuminance values which may be too high for computer work and which resulted in some unacceptable luminance ratios between the VDT screen and the wall behind.

The study thus generally indicated that dark-coloured screens should preferably be used in offices where the window occupies the central field of view of the office worker and where most of the tasks are carried out on the computer. However, artificial lighting should be provided in this case (on the walls and task) and it should also be possible to pull the shading screens up when the outdoor illuminance levels are low. The white screens should be used in offices where the occupant is sitting so that the window is not in the field of view and traditional office tasks are still performed. These shading screens do prevent direct sunlight patches and provide a pleasant and evenly distributed light in the room but the view through the window is completely blocked.

5.2 Simulations with *Radiance*

The impact of six shading devices on daylight quality and on the potential for daylight utilisation in a standard, south-oriented office room was investigated using the simulation program *Radiance*. The daylight quality was evaluated by considering four performance indicators: the absolute work plane illuminance, the illuminance uniformity on the work plane, the absolute luminance values in the room, and the luminance ratios between the work plane (paper task), VDT screen and surroundings. The potential for daylight utilisation was assessed by studying the daylight factors and the manual switch-on probability according to a formula introduced by Hunt (1980).

The shading devices studied, which were all located on the exterior side of the window, included:

- a white awning;
- a dark blue awning;
- a fixed overhang with slats;
- an aluminium venetian blind with horizontal and 45° slats;
- a white diffusing screen;
- a grey screen with a dominant specular (direct) transmittance.

The analysis was based on simulations under perfectly (CIE) sunny sky conditions (on June 21, September 21 and December 21, at 09.00, 12.00 and 15.00 hours) and under a (CIE) overcast sky. The simulated office room was identical to the experimental rooms of the Daylight Laboratory at the Danish Building and Urban Research Institute in Hørsholm, Denmark.

The results of the study indicated that the shading devices studied may be divided into three groups:

Group 1:	**Group 2:**	**Group 3:**
Grey screen	45° V. B. (alum.)	Horiz. V. B. (alum.)
	White screen	Overhang
	Blue awning	White awning

The devices of Group 3 provided relatively high work plane illuminance levels, acceptable illuminance uniformity on the work plane, and an acceptable daylight factor (> 1 %). They also had a very low manual switch-on probability, which suggests that they offer a high potential for daylight utilisation. Moreover, these devices produced acceptable luminance ratios between the paper task, VDT screen and surroundings, although there was a small percentage of ratios for which the task was too bright compared with the VDT screen, especially in the cases of the white awning and overhang. However, the shading devices of Group 3 generated a significantly higher percentage of high luminance values (> 500 cd/m^2) in the room and at the window compared with the other devices studied, which makes them unsuitable as daylight control devices.

The results further indicated that the grey screen (Group 1) produced unacceptably low work plane illuminance levels and a poorer illuminance uniformity on the work plane compared with the other devices studied. The average daylight factor was also unacceptably low (0.1 %) and the manual switch-on probability very high (94 %), which suggests that this device yields marginal energy savings through daylight utilisation. Moreover, the grey screen yielded a high percentage of unacceptable luminance ratios between the VDT screen and the surroundings and between the VDT screen and the task (paper). The task and surroundings were too dark compared with the VDT screen. However, the grey screen was the only device which prevented luminances above 500 cd/m^2.

Finally, the results indicated that the shading devices of Group 2 (45° venetian blind, white screen, blue awning) produced acceptable work plane illuminance levels for a combination of work and computer work; they yielded acceptable illuminance uniformity on the work plane and a low percentage of luminance values above 500 cd/m^2. Moreover, they also provided acceptable luminance ratios between the task (paper), VDT screen and surroundings but the performance of the white screen was the best among all devices studied for this performance indicator. However, these devices resulted in a low average daylight factor (0.5 %) and a moderate manual switch-on probability, which suggests that some mechanism should be provided to ensure that these devices can be removed (pulled-up) on overcast days. Moreover, note that the blue awning had a much poorer performance in December and did not prevent direct sunlight patches in the room. Also, the white screen resulted in a bright luminous veil at the window, with a luminance above 500 cd/m^2, most of the time. The best performing device was thus the 45° venetian blind.

The results thus suggest that the overhang, white awning and horizontal venetian blind should preferably be used in offices where traditional (paper) tasks are carried out while all the other devices except the grey screen should be used in offices where a combination of paper and computer work is performed. However, since none of these devices but the grey screen totally avoided high luminance values (500 cd/m^2), special care should be taken to avoid placing the workstation in such a way that the window is directly in the field of view of the occupant, especially in the case of the overhang, white awning and white screen. The venetian blind might be the only device which may avoid luminance values above 500 cd/m^2 when the slats are totally closed (but this alternative was not tested here).

Finally, the results of this study indicated that it was much more difficult to obtain acceptable levels of daylight quality in December than in June and September. This is due to the low solar altitudes in the winter, which make it difficult to shade the entire window area and avoid bright sunlight patches in the room. These bright sunlight patches produce high contrasts, poor illuminance uniformity, and poorer luminance ratios between the VDT screen and the surroundings, and there is a risk for disturbing reflections in the VDT screen. This is a special problem in Scandinavian countries and other countries at high latitudes.

Thus, shading devices like overhangs and even awnings are not appropriate as daylight control devices in countries at high latitudes. Devices which can shade the entire window area like screens and venetian blinds are more suitable, especially in offices where the work is mostly computer-based. However, the study showed that not all types of screens provide daylight quality. In this case, an extremely poor performance was obtained with a specular screen (grey screen) while an extremely good performance was obtained with a diffusing screen (white screen). The study thus also indicates that it is essential that the shading device changes the direction of the incoming light rays, by pure diffusion or by redirection (preferably towards the ceiling) of the direct incident light as in the case of the venetian blind. Venetian blinds are perhaps even preferable to screens because they are more flexible since the slat angle can be changed as a function of specific daylight conditions while the view out can be maintained for many slat angle positions. In the case of a white diffusing screen, the view out is totally lost as soon as the sun hits the screen because the screen becomes self luminous and brighter than the outside scene and all contrast in the outside scene is lost.

5.3 Overall performance

Although the shading devices evaluated in the Daylight Laboratory were not the same as the ones modelled in *Radiance*, the results of the simulations seem reasonable compared with the results from the measurements. For example, the Grey screen modelled in *Radiance* was similar to the Plastic screen evaluated in the laboratory and the results from measurements and simulations yielded equivalent conclusions: these screens result in unacceptably low illuminance values and poor uniformity; they do not prevent direct light patches and create unacceptable luminance ratios between the VDT, work plane and surrounding surfaces. Also, the values obtained with simulations for the White screen (with a transmittance of 15 %) were generally lower than the values obtained with measurements for similar diffusing white screens, but the screens evaluated in the laboratory had a higher transmittance (27 and 59 %). They thus yielded much higher illuminance and luminance values in the room. Finally, both studies came to the conclusion that the venetian blind (closed or 45° slats) resulted in the best overall performance for offices with computers.

The results of both studies indicate that the shading systems studied may be divided into three groups as follows (the screen's transmittance is indicated in parentheses; italics indicate that the shading system was evaluated using simulations with *Radiance*):

Group 1:

Black and brown screens (3-13 %)
Grey screen (4 %)

Group 2:

45° V. B. (alum.)
Closed V. B. (white)
White screen (15 %)
Blue awning

Group 3:

Horiz. V. B. (alum.)
Horiz. V. B. (white)
Overhang
White awning
Wh. screens (27-59 %)

Group 1 includes all black and brown screens, which had a transmittance between 3 and 13 %. These screens resulted in unacceptably low illuminance and luminance values in the room and unacceptable luminance ratios between the VDT screen, work plane and surrounding surfaces. Note that the black screen with the highest transmittance (13 %) performed significantly better than the other screens in that group, which all had a transmittance below 9 %. Group 2 includes the venetian blind with closed slats (white) or with the 45° slats (aluminium) as well as the white screen with a transmittance of 15 % and the blue awning. These devices generally provided illuminance and luminance levels which are compatible with work on computer. They also provided a better illuminance uniformity in the room. Note, however, that the blue awning had a very variable performance over the year and failed to prevent direct sunlight patches in the room, especially with low sun angles. Group 3 includes the horizontal venetian blind (white and aluminium), overhang, white awning and white screens with a higher transmittance (27-59 %). These devices yielded high illuminance levels, which make them less suitable for office work with computers. They also failed to prevent direct sunlight patches in the room or the direct view of the bright sky. The white screens and awning exacerbated the glare problem since they turned into a bright luminous veil under direct sunlight, which also completely blocked the view out.

The results thus generally indicate that the venetian blind may be the best daylight control device. Also, a screen with a transmittance of at least 15 % may also be acceptable but the transmittance should not be higher than around 25 % and not lower than 10 %, especially in offices where the work is mostly computer-based.

6 Discussion and conclusions

A few studies about solar shading devices have been presented in this thesis. These studies include a literature review, parametric studies of energy use, the development of design tools, measurements as well as simulations of daylighting in rooms with shading devices. The following conclusions can be drawn from the results of these studies:

1) Shading devices can reduce thermal losses through the window significantly, especially if the device is airtight, sealed around the window, close to the windowpane, has light-coloured or low-e backings and is made of multiple layers.

2) Knowledge about the solar-optical properties of shading devices was still rather scant in 1997 and there was a shortage of models to accurately predict the impact of shading devices on energy use. Great progress has been made in this area since then. Within the Solar Shading Project at Lund University, the total solar transmittance of a large number of common shading systems has been characterised through measurements, and detailed algorithms to accurately predict the impact of most of these devices on energy use have been developed, validated and integrated into a whole building energy simulation program (*Derob-LTH*).

3) Solar-protective (absorbing, reflecting) glazing might be energy-efficient but the relative potential for energy savings depends on the orientation of the facade and on the climate. In general, for orientations and climates which have a significant amount of solar radiation during the winter, higher transmittance glazing or larger glazing areas provide larger energy savings (compared with other facades and climates) because the potential for passive solar utilisation during the winter offsets increases in the cooling demand. This conclusion can only be drawn on condition that larger thermal losses resulting from larger glazing areas or poorer window U-values are compensated for by an increase in the thickness of the insulation around the window or elsewhere in the building.

4) The potential for energy savings is much greater with a simple exterior shading device with a low g value, e.g. a dark blue awning, than with any solar-protective glazing assembly because the shading device can be removed during the winter and the free solar heat gains can be utilised to offset the heating demand. This is a significant factor to consider in Scandinavia and Canada where the heating demand is dominant.

5) It is not necessary that exterior shades provide 100 % shading for steep angles of incidence. The most important is to provide shading when the sun is in front of the window i.e. when the window transmittance and the intensity of the incident beam are highest. For example, in the case of awnings, it was shown that it is not necessary to have very large awnings or awnings with sides since the solar radiation leaking on the side of the awning (at steep angles of incidence) was insignificant with respect to annual cooling loads. The advantage of smaller awnings is that light leakage from the sides of the awning may provide beneficial diffuse daylighting.

6) Simple tools for early design stages must provide detailed information about the solar angle dependent properties of the window and the heating and cooling demand in the building. A simple chart showing the total solar angle dependent transmittance of the window greatly simplifies the design problem and reduces the number of variations which must be studied through computer simulations.

7) Shading devices which project from the exterior facade of the building like awnings and overhangs are not suitable daylight control devices in offices where the work is mostly computer-based because they do not prevent direct sunlight patches in the room and they produce illumination levels which may be too high for computer work. The problem is exacerbated at high latitudes where the sun is just above the horizon in the winter. Vertical devices, which can shade the entire window area like screens and venetian blinds, are preferable and should always be provided in addition to exterior devices like awnings and overhangs.

   An optimum solution might be to combine a very efficient (low g value) exterior shading device like an awning to prevent overheating in the summer, spring and autumn, with an interior device with a high g value like an interior venetian blind or curtain, to control daylighting, even in December. The advantage of using an interior device for daylight control is that interior devices have a higher *g* value and thus have a smaller impact on the useful winter solar heat gains. Moreover, interior devices can be manually controlled and may thus provide higher levels of user-satisfaction. Note also that interior shading devices like curtains are often used for aesthetic reasons.

8) Shading devices should change the direction of the incident light rays, either by pure diffusion or by redirection (preferably towards the ceiling) as in the case of a venetian blind. The best shading devices are the ones which block or redirect direct light and let diffuse lighting come into the building. Shading devices with a strong direct transmittance component like screens with holes, should be avoided. These devices block the diffuse daylighting and let some direct sunlight in, which results in low interior luminance and illuminance levels and bright sunlight patches in the room. This generates high contrasts (poor uniformity), poor visibility and high levels of discomfort.

9) Screens which have an extremely low transmittance (lower than around 10 %) may reduce the daylighting in the room to unacceptably low levels, even if they diffuse light properly. This results in unacceptable illuminance and luminance levels and unacceptable luminance ratios between the VDT screen, the paper task and surroundings. On the other hand, white screens with a fairly high transmittance (higher than around 25 %) may yield light levels than are unsuitable for work on computer. A screen transmittance of around 15 % appears to be optimum for a south-oriented room with a medium window size (24 % of exterior wall area; 12 % of floor area).

6.1 Future research

Although large research projects like the Solar Shading Project at Lund University have greatly increased and deepened knowledge about solar shading devices and their impact on energy use, much research remains in this field. Some of the most important areas that need to be explored further are summarised below:

1) More research is needed to assess the impact of shading devices on the window U-value with double-, triple-pane and (low-e) coated windows. These effects need to be included in energy simulation programs.

2) Algorithms that predict the impact of shading devices on the indoor daylighting levels need to be developed further and included within whole building energy simulation programs so that the impact of daylighting on energy use for lights can be studied as well. Some work in this direction has already been initiated by Bülow-Hübe and Källblad (Bülow-Hübe, 2001) within the Solar Shading Project. These algorithms need to be further developed and validated and the whole building energy simulation program needs to be further developed to allow modelling of movable devices i.e. devices which go up or down as a function of overheating or daylighting in the room.

3) More parametric studies of energy use in buildings including energy use for heating, cooling and lighting need to be carried out, for a variety of climates, orientations and building types. Combinations of shading devices (interior and exterior), movable shading devices and shading devices combined with special (solar-protective, low-e) glazing should also be studied. The parametric studies presented in this thesis are much too limited as a background for design guidelines. Much work remains in this area.

4) Control strategies for shading devices and artificial lighting need to be studied through measurements and through computer simulations.

5) The simple design tools presented in this thesis should be included in a computer program such as *Parasol-LTH*. They should also be extended so that the optimal geometry of the shading device meeting a specific shading mask or monthly g value could be generated automatically. These tools also need to be tested further to see if they are really useful in a real design situation and if they can be accepted by the design professionals.

6) The daylight studies should be supplemented with behavioural studies (i.e. with real human subjects). This would make it possible to verify whether the protocol for evaluating daylighting quality is adequate. Behavioural studies might show, for example, that other performance indicators need to be included in the analysis or that the requirements used in this study were too severe for situations with daylighting.

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Article I

A METHOD TO DEFINE SHADING DEVICES CONSIDERING THE IDEAL TOTAL SOLAR ENERGY TRANSMITTANCE

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Abstract – A method to determine the optimum total solar energy transmittance (G value) of a shading device is presented. The method consists in determining the ideal hourly G value of the shading device from the results of one energy simulation for the room or building with a bare window (no shading device). These hourly G values are then converted to monthly and annual values using weighted averages. One example is provided where the method is used to determine the optimum properties of a screen to be installed on a south-oriented office room in Stockholm (Sweden). It is shown that the method allows to predict the optimum monthly and annual G values with a relative accuracy. The method is therefore useful to identify the optimum shading device properties rapidly, avoiding many iterations in the simulations.

1. INTRODUCTION

In buildings with artificial cooling installations, large energy savings can be achieved by installing solar shading devices above windows. According to a recent literature review (Dubois, 1997), solar shading can reduce a building's cooling demand by up to 89%. Shading devices are also useful for controlling daylighting levels, privacy and avoid glare from windows (Littlefair, 1999).

In cold countries, one drawback of using shading devices is the risk to reduce useful solar gains during the winter and increase the heating demand. One study (Dubois, 1999) showed that a fixed (i.e. in place year round) awning can increase a room's heating demand by 31% (28 kWh/m^{2}year) in Stockholm (Sweden). This study concluded that it is essential to use shading devices that can be removed (or pulled up) during the heating season. This is unfortunately not always possible due to the costs and maintenance associated with movable shades and fixed shading devices are still very common in cold countries.

One way to take into consideration both heating and cooling loads in the design of shading devices is to study their impact on energy use or indoor temperatures using a dynamic energy simulation program. The advantage of using energy simulations is that most of the complex thermal and radiative processes between the building, the shading device and the outdoor environment are considered in the calculations. The most advanced programs take into consideration both direct and diffuse solar radiation, the window's solar angle dependent properties and longwave sky radiation. Some programs e.g. *Derob-LTH* (Källblad & Wallentén, 1999) can even model the thermal exchanges between the window and the shading device. It follows that the building's hourly heating and cooling demand is predicted very accurately.

The normal procedure with energy simulation programs consists in

1) building a base model and perform an energy simulation;
2) modify the base model and repeat the energy simulation to investigate the impact of this modification on energy use or indoor temperatures;
3) repeat the last step until a satifactory solution is reached.

Although this procedure normally yields an accurate solution, it is quite laborious since a large number of simulations are needed before the optimum solution is reached. For example, in a study about awnings (Dubois, 1999), 31 simulations had to be performed to identify the optimum shading solution for one single room and orientation. In a real building, which usually has a variety of window types and orientations, many more simulations are required.

This paper presents a more rapid method to identify the optimum shading device using energy simulations. The method consists in determining the ideal hourly total solar energy transmittance (G value) of the shading device from the output data provided by one simulation for the room or building with a bare window (no shading device). These hourly G values are then converted into monthly and annual values using weighted averages. This paper presents this method and shows, through one example, that it predicts the optimum shading device's monthly and annual G values with an acceptable accuracy.

2. METHOD

2.1 Description of the method

One factor which characterises a window and shading device assembly is the total solar energy transmittance of the system, which is also called the G value. The G value expresses how much solar radiation is absorbed and transmitted through the system (window plus shading device) and becomes heat in the building. It includes both the primary and secondary transmittance and can thus be expressed as follows:

$$G_{sys} = \frac{Q_{sun}}{I_G \cdot A_w} \tag{1}$$

where G_{sys} is the system's (window plus shading device) total solar energy transmittance, Q_{sun} is the total solar gain in the building, I_G is the global solar radiation on the facade and A_w is the window area.

Since the total transmittance of a system is the product of the transmittance of each part of the system, the *G* value of the shading device (G_{sh}) can be determined as follows:

$$G_{sh} = \frac{G_{sys}}{G_{win}} \tag{2}$$

where G_{win} is the *G* value of the window, which can be determined from measurements or using "exact" calculations, semi physical models, empirical models or template models (Karlsson et al., 1999).

Similarly to the shading coefficient, the shading device's *G* value (G_{sh}) is a measure of the effectiveness of the shading device "to shade windows". A "good" shading device has a low *G* value since only a small portion of the incident radiation is absorbed and transmitted by the shading device and becomes heat in the building. A "poor" shading device has a high *G* value since it lets most of the incident radiation reach the window. Thus, in the middle of the summer, a low *G* value (~0) is usually desirable to avoid overheating while during the winter, a high *G* value (~1) is preferable because solar heat gains are useful to offset heating loads. During the spring and autumn when outdoor temperatures are low but solar radiation is high, some solar energy might be desirable to maintain the indoor comfort temperature without having to artificially heat the building. On the other hand, too much solar radiation might result in the need for artificial cooling. During these periods, the optimum *G* value is the one which maintains the indoor comfort temperature with as little as possible energy expenditures. The ideal *G* value to achieve a low energy use is therefore variable throughout the day and the year and depends on the outdoor climate (temperature and solar radiation) and on the desired indoor temperature and internal loads.

One simple way to determine the ideal *G* value (G_i) for the shading device is to analyse the output data obtained from one energy simulation for the room or building with a bare window (no shading device) in the following way:

Given that $I_G > 0$ (daytime),

$$\text{if} \quad Q_{cool} \geq Q_{sun} \quad \text{then} \quad G_i = 0 \tag{3}$$

$$\text{if} \quad Q_{cool} < Q_{sun} \quad \text{then} \quad Gi = \left[1 - \frac{Q_{cool}}{Q_{sun}}\right] \tag{4}$$

$$\text{if} \quad Q_{sun} = 0 \quad \text{then} \quad G_i = 1 \tag{5}$$

$$\text{if} \quad Q_{cool} = 0 \quad \text{then} \quad G_i = 1 \tag{6}$$

where Q_{cool} is the hourly cooling load. Thus, if the cooling demand (Q_{cool}) is equal to or larger than the solar heat gain (Q_{sun}), all the heat from the sun should be avoided and the ideal *G* value for the shading device (G_i) is 0. On the other hand, if Q_{cool} is smaller than Q_{sun}, it means that a part of Q_{sun} is lost through the building envelope. This occurs most often during the spring and autumn when the outdoor temperature is low and solar radiation is high. In that case, G_i corresponds to the portion of Q_{sun} lost through the building envelope, which is the difference between Q_{sun} and Q_{cool}. If Q_{sun} is equal to 0, there are no solar heat gains and no shading device is required; G_i is thus equal to 1. Finally, if Q_{cool} is equal to 0, there is no cooling load and G_i is 1 since the solar gains are useful either to maintain the comfort temperature or to offset the heating demand.

Since the values (Q_{sun}, Q_{cool}, I_G) necessary to determine G_i are normally provided by energy simulations, it is possible to calculate the G_i values at each hour of one year from the output data provided by a single energy simulation for the room or building with a bare window (no shading device). As an example, these hourly values have been determined for a south-oriented office room in Stockholm on a typical day in April. These values are reported in Table 1 and illustrated in Fig. 1. Fig. 1 shows that G_i varies throughout the day with maximum values at night and minimum values in the afternoon. The ideal shading device is thus different at each hour, which is in practice impossible to achieve with a flat shading device (screen) unless a switchable material is used.

The hourly G_i values obtained can be converted into monthly or annual values depending on the type of shading device to be installed (seasonal, fixed). A simple way to convert hourly G_i values into monthly or annual values is to use weighted averages. In this article, the total energy use (Q_{tot}), which in this case is the sum of heating and cooling loads, and the solar heat gains (Q_{sun}) were alternately used as weighting factors and the impact of using each factor on predicted monthly and annual G_i values is discussed. With Q_{tot} as weighting factor, the following equations were used to determine the monthly (*mth*) and annual (*year*) G_i values:

$$G_i(mth) = \frac{1}{\sum\limits_{mth} Q_{tot}(hour)} \cdot \sum\limits_{mth} Q_{tot}(hour) \cdot G_i(hour) \qquad (7)$$

$$G_i(year) = \frac{1}{\sum\limits_{year} Q_{tot}(mth)} \cdot \sum\limits_{year} Q_{tot}(mth) \cdot G_i(mth) \qquad (8)$$

The same equations were used with Q_{sun} instead of Q_{tot} as weighting factor.

Table 1 G_i values for a south-oriented office room in Stockholm on a typical day in April.

Hr	T_{out} (°C)	$I_G{*}A_w$ (W)	Q_{sun} (W)	Q_{heat} (W)	Q_{cool} (W)	G_i
1	-1.5	0	0	194	0	..
2	-2.4	0	0	212	0	..
3	-2.7	0	0	223	0	..
4	-2.4	0	0	226	0	..
5	-3.5	0	0	244	0	..
6	-3.6	51	21	247	0	1.00
7	-1.3	172	68	218	0	1.00
8	-0.8	607	258	170	0	1.00
9	1.1	1081	476	0	115	0.76
10	2.5	1500	669	0	228	0.66
11	3.2	1482	666	0	280	0.58
12	4.2	1864	840	0	388	0.54
13	4.9	1925	870	0	454	0.48
14	5.4	1716	782	0	472	0.40
15	5.5	1330	606	0	449	0.26
16	5.3	909	418	0	393	0.06
17	4.9	397	195	0	313	0.00
18	4.3	88	59	0	16	0.73
19	4.3	22	27	21	0	1.00
20	3.5	0	4	56	0	..
21	2.3	0	2	87	0	..
22	2.2	0	2	105	0	..
23	2.1	0	1	120	0	..
24	2.3	0	0	131	0	..

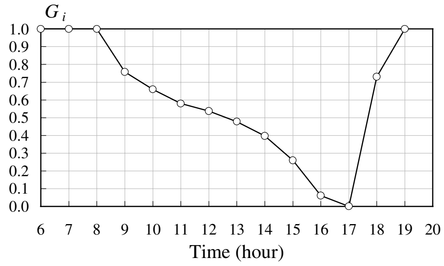

Fig. 1 G_i values for a south-oriented office room in Stockholm on a typical day in April.

2.2 Example

The method presented in the previous section was used to determine the monthly and annual G_i values for an exterior screen to be installed on a south-oriented office room in Stockholm. A parametric study was then carried out to determine if the proposed method yielded the optimum screen properties. In the parametric study, the G value of the screen was varied by 0.1 increments between 0 and 1 and the impact of these variations on monthly and annual energy use were investigated.

The computer program used for the energy simulations as well as the office room where the screen was installed are described in the following sections.

2.2.1 Energy simulation program

The energy simulation program *Derob-LTH* was used to carry out the parametric study and to determine the hourly G_i values according to the proposed method. *Derob-LTH*, which is an acronym for Dynamic Energy Response of Buildings, originates from the University of Texas (Arumi-Noé, 1979) but has been under continuous development at Lund University's Department of Building Science (Kvist, 1998; Källblad, 1999). The program uses hourly data for the exterior temperature and the solar radiation intensity and updates the solar position four times every month. It has been recently supplemented with advanced algorithms for windows and exterior shading devices (Källblad & Wallentén, 1999). These window and shading algorithms have the following characteristics:

- Coarse ray tracing and Fresnel calculation of the direct radiation;
- View factor and Fresnel calculation of the diffuse radiation;
- One thermal node for each pane;
- Shading device transmits and reflects diffusely;
- One thermal node approximating the thermal balance for all shading devices;
- Long wave sky radiation included.

The shading and window models in *Derob-LTH* have been validated experimentally using two full-scale guarded hot boxes exposed to the natural climate. A comparison between measured and simulated energy for a dark and a light awning has shown a maximum error of 3% with respect to the incident solar radiation (Källblad & Wallentén, 1999).

2.2.2 Office room

The screen was installed on the exterior side of the window of a standard office room. The office room was a 2.9-m wide by 4.2-m deep rectangular space with a 1.8-m wide by 1.3-m high, triple-pane, clear glass window (Fig. 2).

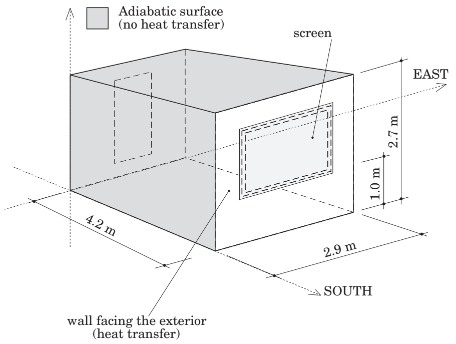

Fig. 2 Office room.

The window had a U-value of 1.88 W/m^2°C and a G value of 0.67 at normal incidence. The exterior wall was a standard construction with respect to Swedish norms with a U-value of 0.18 W/m^2°C. The room was assumed to be surrounded by office space at the same temperature. Thus, all "interior" walls were modelled as adiabatic surfaces. A free horizon with no obstruction and a ground reflectance of 20% were assumed.

The room had a constant infiltration rate of 0.1 ach and a ventilation rate of 10 l/s during weekdays at normal office hours (8-17) and 5 l/s the rest of the time. Internal heat gains from one occupant (90 W), a computer and monitor (120 W) and energy-efficient lighting (10 W/m^2) were assumed during work hours. A constant indoor temperature of 22°C was assumed throughout the year to simplify the study.

3. RESULTS

3.1 Determination of the G_i values

The G_i values were determined from the energy simulation for the screenless office room using the method described in Section 2.1. These hourly G_i values (Q_{tot} weighted) are presented in Table 2 and in Fig. 3. In Fig. 3, the cooling months (May-September) are presented separately to facilitate the reading of the diagrams.

The values in Table 2 show that complete shading (G_i = 0) is only required during some hours in the afternoon from May to September. The rest of the time, either no shading (G_i = 1) or partial shading (G_i = 0-1) is desirable.The lowest hourly G_i values are "displaced" towards the right and bottom of Table 2. The displacement towards the right is due to the Earth's thermal inertia, which yields an asymmetrical cooling season with respect to the summer solstice while the displacement towards

Table 2 Hourly G_i values (Q_{tot} weighted) for each month.

Hour	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
1	..	..	..	..	..	..	..	..	..	..	..	..
2	..	..	..	..	..	..	..	..	..	..	..	..
3	..	..	..	..	..	0.99	0.99	..	..	..	..	..
4	..	..	..	..	1.00	0.98	0.97	1.00	..	..	..	..
5	..	..	..	1.00	1.00	0.95	0.97	1.00	..	..	..	..
6	..	..	1.00	1.00	1.00	0.93	0.93	1.00	1.00	..	..	..
7	..	..	1.00	1.00	0.99	0.88	0.83	1.00	1.00	1.00	..	..
8	..	1.00	1.00	1.00	0.95	0.81	0.73	0.99	1.00	1.00	1.00	..
9	1.00	1.00	1.00	0.55	0.10	0.02	0.01	0.02	0.13	0.42	1.00	1.00
10	1.00	1.00	0.99	0.55	0.15	0.03	0.01	0.08	0.17	0.40	0.97	1.00
11	1.00	1.00	0.94	0.50	0.15	0.04	0.02	0.08	0.17	0.39	0.92	1.00
12	1.00	1.00	0.85	0.43	0.13	0.04	0.01	0.06	0.16	0.34	0.86	0.99
13	1.00	0.99	0.80	0.39	0.08	0.02	0.01	0.04	0.10	0.31	0.80	0.99
14	1.00	0.99	0.74	0.31	0.04	0.01	0.00	0.01	0.04	0.23	0.77	0.99
15	1.00	0.99	0.71	0.21	0.01	0.00	0.00	0.00	0.02	0.10	0.75	1.00
16	1.00	1.00	0.70	0.09	0.00	0.00	0.00	0.00	0.00	0.05	0.82	1.00
17	..	1.00	0.69	0.06	0.00	0.00	0.00	0.00	0.00	0.04	1.00	..
18	..	..	1.00	0.92	0.18	0.14	0.05	0.15	0.27	0.94	..	..
19	..	..	1.00	0.97	0.25	0.16	0.04	0.25	0.64	..	..	..
20	..	..	..	0.99	0.40	0.22	0.05	0.44	..	..	..	..
21	..	..	..	..	0.70	0.33	0.10	0.60	..	..	..	..
22	..	..	..	..	..	0.56	0.55	..	..	..	..	..
23	..	..	..	..	..	..	..	..	..	..	..	..
24	..	..	..	..	..	..	..	..	..	..	..	..

the bottom of Table 2 is due to the building's thermal inertia.

Fig. 3 shows that the G_i value is dependent both on the outdoor climate (solar radiation and temperature) and the interior conditions (internal heat loads and ventilation) since daily and monthly variations can be observed. The G_i value is 1 most of the time outside work hours but decreases dramatically at the beginning of the work day (08.00 hours) due to a rise in internal heat gains which contribute to an increase in the cooling demand. Shading is then required to take away some heat from the sun. The G_i value continues to decrease as the day progresses and reaches a minimum at the end of the work day i.e. around 17.00 hours. At 18.00 hours, it suddenly increases due to the removal of internal loads and remains high after work hours for most months.

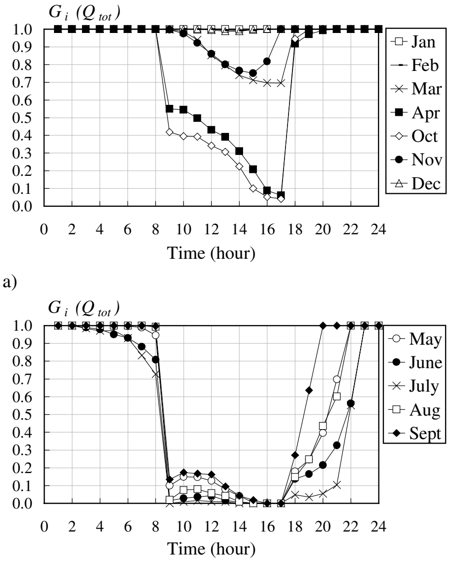

Fig. 3 G_i values predicted for each hour of a) the autumn, winter and spring and b) the summer months.

The monthly G_i values obtained using Q_{tot} and Q_{sun} as weighting factors are presented in Table 3. Table 3 shows that no shading (~1) is preferable in December, January and February and that close to complete shading (~0) is required in June, July and August. A low G value is desirable between May and September while a high G value is required in March and November. Table 3 also shows that the two weighting factors yield rather close values. Using Q_{tot} as the weighting factor yields slightly higher values during the winter and slightly lower values during the summer.

Table 3 Monthly G_i values as a function of weighting factor (Q_{tot} or Q_{sun}).

	Weighting factor	
Month	Q_{tot}	Q_{sun}
Jan	1.00	0.99
Feb	1.00	0.98
Mar	0.92	0.81
Apr	0.57	0.50
May	0.17	0.17
June	0.11	0.12
July	0.04	0.10
Aug	0.11	0.13
Sept	0.14	0.19
Oct	0.35	0.45
Nov	0.88	0.84
Dec	1.00	0.98
Annual	0.31	0.35

The annual G_i value obtained is 0.31 using Q_{tot} as the weighting factor and 0.35 with Q_{sun}. Using Q_{sun} thus yields a slightly higher annual G_i value than using Q_{tot}.

3.2 Parametric study

The results of the parametric study are summarised in Fig. 4, which shows the total energy use (sum of heating and cooling loads) for each month as a function of the screen's G value. Fig. 4 shows that total energy use was minimum with a G value of 1 in January, February, March, November and December. In May, June, July, August and September, the total energy use was minimum with a G value of 0, while in April and October, a G value of 0.4-0.6 yielded the lowest total energy use. However, note that in January, April and October, a variation of the G value had a very small influence on total energy use.

The monthly optimum G values obtained in the parametric study are compared in Fig. 5 with the monthly G_i values predicted by using the method. Fig. 5 shows that the method allows to predict the optimum monthly G value with an acceptable accuracy, especially for G_i values weighted according to Q_{tot}. The largest discrepancies between predicted and simulated values are for the summer months (May-September). However, Fig. 4 shows that a G value of 0-0.1 yielded approximately the same total (lowest) energy use (less than 0.01% difference). The G_i values (Q_{tot} weighted) of Fig. 5 are thus within a region of very low total energy use and are acceptable. Some discrepancies between the predicted and simulated values are also found in March, October and November, even with Q_{tot} as weighting factor. Again, Fig. 4 shows that a G value of 0.9-1.0 yielded approximately the same total (lowest) energy use (less than 0.01% difference), which means that the G_i values (Q_{tot} weighted) of Fig. 5 are of acceptable accuracy.

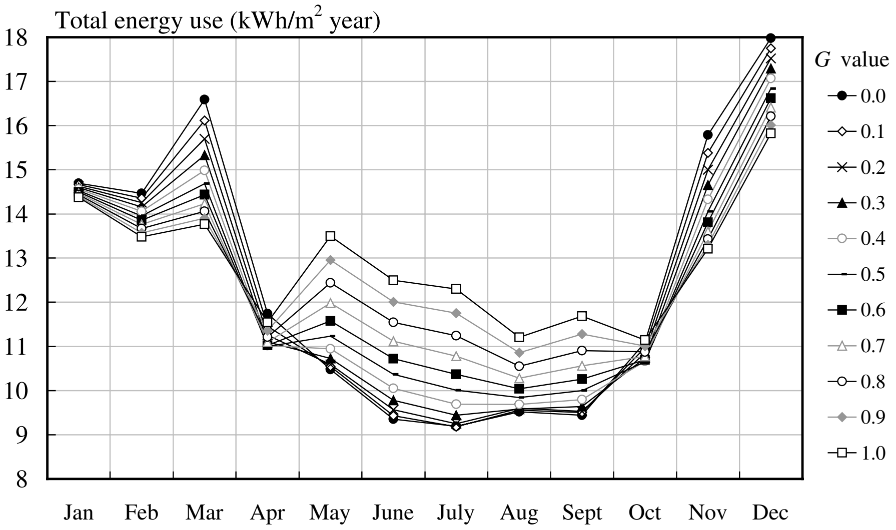

Fig. 4 Total monthly energy use (sum of heating and cooling loads) (kWh/m^{2}year) as a function of the screen's *G* value obtained with the parametric study.

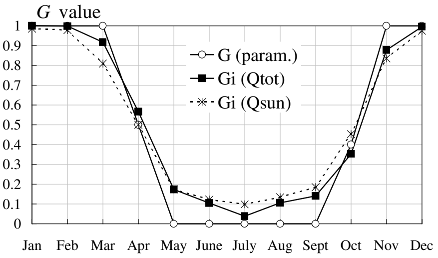

Fig. 5 Optimum *G* value obtained in the parametric study compared with the G_i values weighted according to Q_{tot} and Q_{sun}.

The incremental annual energy use as a function of the screen's *G* value is shown in Fig. 6. This Figure also shows the annual G_i values obtained using the two weighting methods (Q_{tot} and Q_{sun}).

Fig. 6 shows that the parametric study indicated a minimum annual energy use with a *G* value of 0.4. This value is slightly higher than the ones (0.31-0.35) predicted by using the method described in Section 2.1. However, Fig. 6 shows that a *G* value of 0.3 yielded little additional annual energy use (less than 0.01%) than a *G* value of 0.4. The values predicted by the method are thus of acceptable accuracy.

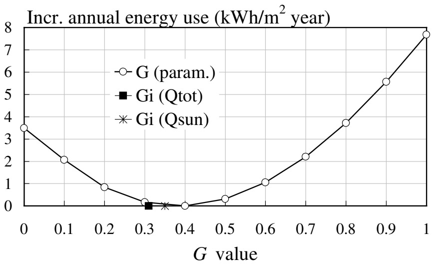

Fig. 6 Total incremental annual energy use as a function of the screen's *G* value obtained with the parametric study compared with the G_i values predicted with the method.

4. DISCUSSION

The comparison between predicted and simulated *G* values (Fig. 5 and 6) shows that the proposed method allows to predict the optimum *G* value for the shading device with an acceptable accuracy, both on a monthly and an annual basis.

On an annual basis, using Q_{sun} as weighting factor predicted the optimum G value more accurately than using Q_{tot}. However, the difference in annual energy use between both predicted G_i values and the simulated G values was negligible (less than 0.01%), which means that both weighting methods allowed to predict the optimum annual G value with an acceptable accuracy.

On a monthly basis, a better fit between predicted and simulated values was obtained by using Q_{tot} instead of Q_{sun} as the weighting factor. This is due to the fact that during the winter, the highest heating load occurs at hours when there is little solar radiation. Weighting the hourly G_i values according to Q_{sun} thus results in a poor fit (especially in March and November). During the summer, a better fit between predicted and simulated values was also obtained by weighting the G_i values according to Q_{tot} instead of Q_{sun}. This occurs because the peak cooling demand is somewhat delayed with respect to the peak solar gains. Weighting the G_i values according to Q_{sun} thus also results in a poor fit.

5. CONCLUSIONS

A simple method to determine the optimum total solar transmittance (G value) of a shading device was presented. The method consists in determining the ideal hourly G value of the shading device from the output data provided by one energy simulation for a room or building with a bare window (no shading device). These hourly G values are then converted into monthly and annual values using weighted averages.

The proposed method was used to determine the optimum G value of a screen to be installed on a south-oriented office room in Stockholm. A parametric study was then carried out to verify whether the method allowed to predict the optimum G value with sufficient accuracy.

It was found that the method did predict the optimum G value both on an annual and monthly basis with an acceptable accuracy. The annual G value was predicted with more accuracy using the solar heat gains (Q_{sun}) as the weighting factor while the monthly values were predicted more accurately using the total energy use (Q_{tot}) as weighting factor in the calculations. However, the discrepancies between predicted and simulated values were not significant because both predicted and simulated G values yielded approximately the same total energy use (less than 0.01% difference).

The proposed method is simple and could easily be implemented in an energy simulation program as a diagnosis tool to use prior to simulations. This would reduce the amount of simulations needed to determine an optimum shading device. The method can also be used to select shading devices which have documented monthly and annual G values. This is the case for some types of awnings, overhangs, exterior venetian blinds and screens, which have been monitored by Wallentén (1999).

The method could be extended to include the lighting energy use in the calculation of the optimum G value. Energy costs for lighting usually account for a large part of the total energy costs in office buildings (40% according to Slater, 1997) and the use of shading devices is likely to result in an increase in the use of artificial lighting. This aspect should thus be considered.

Finally, the method could also be supplemented with algorithms that calculate the optimum geometry of the shading device as a function of the ideal G value. In this paper, a simple screen was assumed since it produces a constant shading pattern on the window. In a real building, other types of shading devices like awnings or overhangs might be preferred because they allow a view out through the window. Another advantage of using these types of devices is that their geometry can be defined so that their G value closely matches the monthly and hourly G values defined by using the method.

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Article II

A SIMPLE CHART TO DESIGN SHADING DEVICES CONSIDERING THE WINDOW SOLAR ANGLE DEPENDENT PROPERTIES

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Abstract – A simple chart useful to design shading devices is presented. The chart, which is complementary to existing solar path diagrams, provides additional information about the window's solar angle dependent properties and its geometrical relationship to the sunbeam. This information allows to make meaningful hypotheses about the optimum geometry of the shading device. Two examples are provided where the chart is used to define the geometry of an awning on a south- and west-oriented office room in Stockholm. The examples show that the chart is useful to restrict the early design hypotheses and identify the optimum awning geometry at an early design stage.

1. INTRODUCTION

Solar shading devices can substantially reduce the cooling load of buildings. According to a recent literature review (Dubois, 1997), this reduction is between 23-89% depending on the type of shading device used, the building orientation, the climate, etc.

In order to save energy, shading devices should be integrated to a building's facade at an early design stage. This can be achieved using "traditional" design tools like solar path diagrams and shading masks or special computer programs that automatically "generate" the optimum shading device geometry as a function of a set of input parameters (e.g. orientation, latitude).

1.1 Traditional tools

Although there exist numerous design methods based on solar path diagrams (Dourgnon, 1965; Van den Eijk, 1965; Markus & Morris, 1980; Etzion, 1992), the Olgyays' (1957) and Mazria's (1979) methods are probably the most popular ones. In both the Olgyays and Mazria's design methods the building's overheating period is plotted onto the solar path diagram and a shading "mask" that avoids direct sun during the overheating period is defined.

The main difference between the two methods is the kind of solar projection used. The Olgyays used a projection of the sun onto a horizontal plane parallel to the ground (Fig. 1) while Mazria used a projection onto a vertical cylinder (with the long axis perpendicular to the ground). By "unfolding" the cylinder, a two-dimensional diagram is obtained, where the abscissa and ordinate represent the solar azimuths and altitudes and where the curves radiating away from the south represent the solar time (Fig. 2). This projection is advantageous for studies of facade elements like windows and shading devices since the sun's projection is viewed "parallel" to the building facade.

Traditional methods have some limitations: their accuracy is limited by the size of the charts and they yield shading devices that are larger than necessary since they are only capable of returning a "binary" answer (Etzion, 1992). This is due to the fact that they indicate an "unshaded" condition even when a small area of the opening is lit by direct sun and a "shaded" condition the rest of the time.

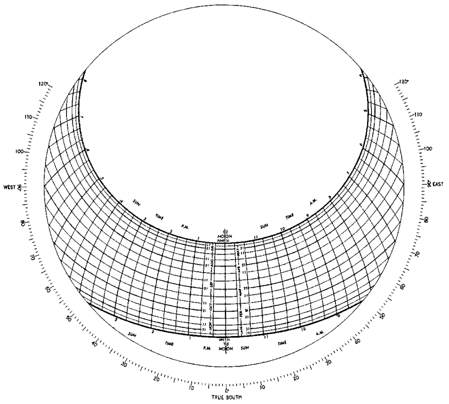


Fig. 1 Solar path diagram used by the Olgyays (1957).

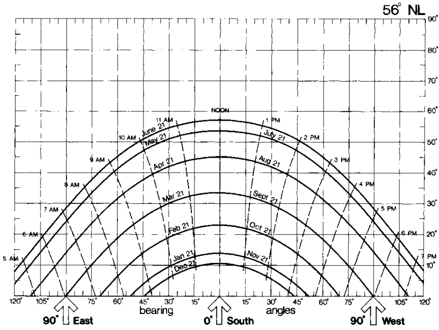


Fig. 2 Solar path diagram used by Mazria (1979).

Despite these limitations, traditional methods are still used and taught in many schools of architecture and a number of computer programs based on these methods have been developed recently (Bouchlaghem, 1996; Oh and Haberl, 1997; Kensek et al., 1996). Methods based on charts have the advantage of being simple and straightforward: they show the relationship between the solar path, the overheating period and the required shade in one single picture.

1.2 Computer tools

Many computer design tools for shading have been developed during the past decades. These tools are in essence similar to traditional tools but have the main advantage that the shading device geometry is automatically "generated" by the program.

One of the first computer design tools for shading was proposed by Shaviv (1975, 1984). This program indicates the shape of the shading device that prevents direct radiation from reaching the window during each month. A similar program, which provides one annual solution by subtracting a summer from a winter design day funnel, was later proposed by Arumi-Noé (1996). More recently, a program combining simulation, generation and optimisation routines was developed by Kabre (1999). This program provides a 3D image of the optimum exterior fixed shading device, which is determined by weighting the "shading" versus "heating" efficiency of the window-shade combination. The optimum solution is determined from the results of energy simulations and a Pareto optimisation.

1.3 Limitations of the existing tools

One limitation of most existing design tools is that they are based on the *incident* (not *transmitted*) solar radiation on the window. The only one who considered the window transmission and absorption properties is Petherbridge (1965). However, he used horizontal projections of the solar path (similar to the Olgyays) and presented the window transmittance and absorptance separately, which make it difficult to use his charts in practice. Kabre (1999) also considered the window transmittance. However, his program takes this parameter into consideration in the simulation routine *after* the shading devices have been generated based on the *incident* sun.

Considering *incident* instead of *transmitted* radiation is equivalent to attributing an equal "weight" to all angles of incidence. This will invariably yield shading devices larger than necessary since all angles of incidence must be covered. In reality, incidence angles close to the window normal usually have more impact on the building's annual energy use since a surface perpendicular to the sun receives the maximum amount of solar radiation and since the window total solar transmittance is maximum around the window normal.

Oversized shading devices are less economical and reduce both the view out through the window and the daylighting in the building. It is well known that a reduction in interior daylighting levels usually yields an increase in the use of artificial lighting, which results in an increase in the cooling load to remove the internal heat gains from lights.

In this article, a simple chart relating the solar path to the window solar angle dependent properties is presented. The chart, which is based on Mazria's (1979) solar path projections, can be used at an early design stage to identify the hours during the day and year when solar radiation is likely to cause overheating in the building.

This article presents the new chart and shows how it can be used in practice by providing an example where the geometry of an awning is defined for a south- and west-oriented office room in Stockholm (Sweden). In this example, the awning's geometry is further studied using dynamic energy simulations. The aim of the simulations is to identify with precision the optimum awning geometry and compare it with the geometry suggested by the chart.

2. METHOD

This section is divided in two parts. The first part explains how the new chart was developed while the second part describes the method and simulations used in the example.

2.1 A new chart for the design of shading devices

Although both direct and diffuse solar radiation are responsible for solar heat gains through windows, in most cold and temperate climates, it is preferable to define shading devices according to direct radiation since

1) diffuse radiation is desirable most of time as a source of daylighting in the building;
2) direct radiation is dominant on clear days when shading is needed.

The chart proposed in this paper is therefore based on direct solar radiation. However, in more extreme climates (hot humid), shading from diffuse radiation might also be desirable and should be considered in the design of shading devices. The diffuse component should also be considered when the shading device is mainly used for glare control.

When direct solar radiation hits a window, two factors contribute in reducing the amount of energy admitted into the building: the incidence angle between the sun beam and the window surface and the window total solar energy transmittance (also called the g-value or solar heat gain coefficient), which is also a solar angle dependent property.

2.1.1 The incidence angle

A surface perpendicular to the sun beam receives the greatest amount of energy. As the sun beam moves away from the window normal, the energy received by the surface decreases. The intensity (I_θ) of solar radiation on the window surface can be determined from the intensity of the direct normal radiation (I_{DN}) according to:

$$I_\theta = I_{DN} \cos\theta \qquad (1)$$

where θ is the angle of incidence of the sun beam. Since the relationship between I_θ and I_{DN} is a constant (k_θ) for a given angle of incidence (θ), the following can be written:

$$k_\theta = I_\theta / I_{DN} = \cos\theta \qquad (2)$$

Note that this relationship holds for all directions with respect to the window surface.

2.1.2 The window g-value

The window g-value indicates which portion of the incident solar radiation is absorbed and transmitted by the window and becomes heat in the building. It includes both the primary and secondary transmittance i.e. the energy absorbed by the glazing and reradiated to the building interior.

The g-value varies according to the sun's incidence angle with respect to the window normal. For most ordinary glazings, the transmittance is maximum around the normal, starts declining at 50° and reaches a minimum at 90° as shown in Fig. 3.

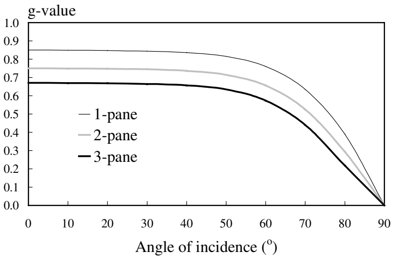


Fig. 3 The g-value (g_θ) for single-, double- and triple-pane clear glass windows as a function of the angle of incidence (calculated according to Karlsson & Roos, 1999).

The solar angle dependent g-value can be imagined as a cone valid for each point of the window (Fig. 4). Since for each cone or angle of incidence (θ) corresponds a specific g-value (g_θ), the set of solar altitudes (ALT) and azimuths (AZ) corresponding to a specific g_θ can be calculated using the fundamental geometrical relationship:

$$\cos(ALT) \cdot \cos(AZ - \phi) = \cos(\theta) \qquad (3)$$

where ϕ is the orientation of the facade (or facade normal) from the same reference direction as the solar azimuth (AZ). Note that the sun is behind the facade when $|AZ - \phi| > 90$.

The set of solar altitudes and azimuths obtained for each specific g_θ can be plotted according to Mazria's solar projection and superimposed on the solar path diagram. This superposition is shown in Fig. 5 for a vertical, south-oriented, triple-pane, clear glass window. Fig. 5 shows a set of concentric, distorted circles, where the centre represents any point at the surface of the window. If the g-value is normalised using $g = g_\theta / g_0$, the inner circle delimits the solar positions for which $g > 0.9$; the second circle includes $g > 0.8$; the third circle is for $g > 0.7$, etc.

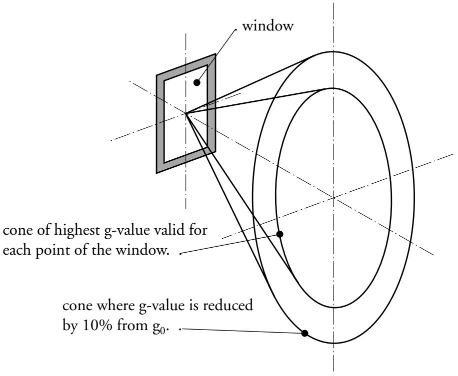


Fig. 4 The window's solar angle dependent g-value (g_θ) can be imagined as a series of cones valid for each point of the window surface.

2.1.3 A cosine weighted g-value

For convenience, the k- and g-values introduced in the previous sections can be combined into one single value, which we will call the Gcos-value or cosine weighted solar angle-dependent g-value. The Gcos-value ($Gcos_\theta$) at incidence angle θ can be calculated as follows:

$$Gcos_\theta = k_\theta \cdot g_\theta \qquad (4)$$

Since $Gcos_\theta$ is a constant for a given angle of incidence (θ), it can thus also be imagined as a series of cones pointing towards the window. The projection of these cones onto Mazria's solar path diagram yields Fig. 6. Assuming that the Gcos-value is normalised using $Gcos = Gcos_\theta / Gcos_0$, the inner circle encompasses the region of maximum values ($Gcos > 0.9$); the next circle is for $Gcos > 0.8$; the third circle is for $Gcos > 0.7$, etc.

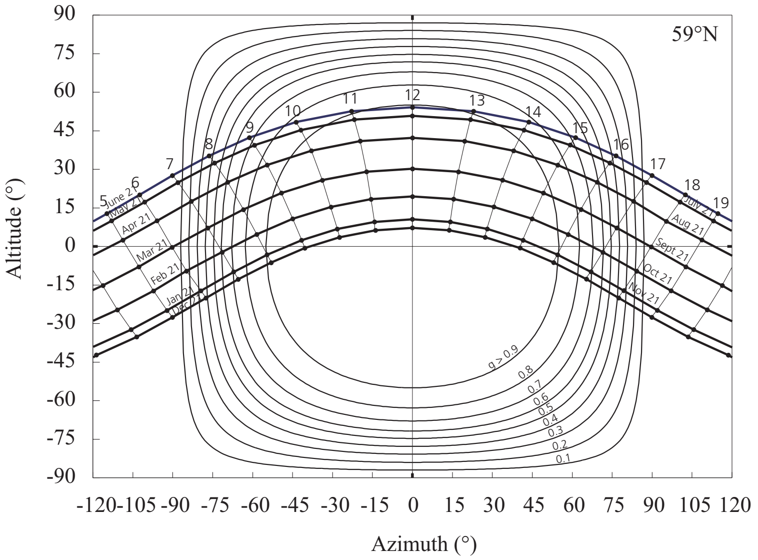


Fig. 5 Chart showing the normalised g-values for a vertical, south-oriented, triple-pane, clear glass window. The chart is superimposed on the solar path diagram for latitude 59°N.

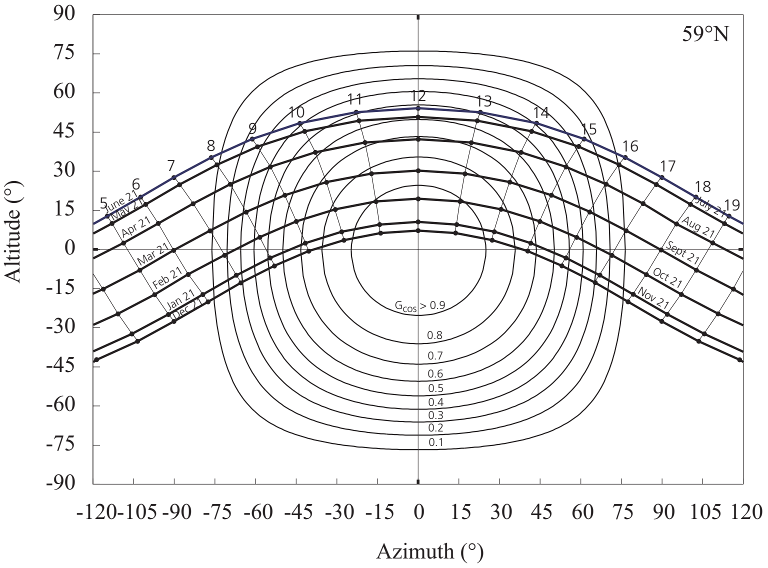


Fig. 6 Chart showing the normalised Gcos-values for a vertical, south-oriented, triple-pane, clear glass window. The chart is superimposed on the solar path diagram for latitude 59°N.

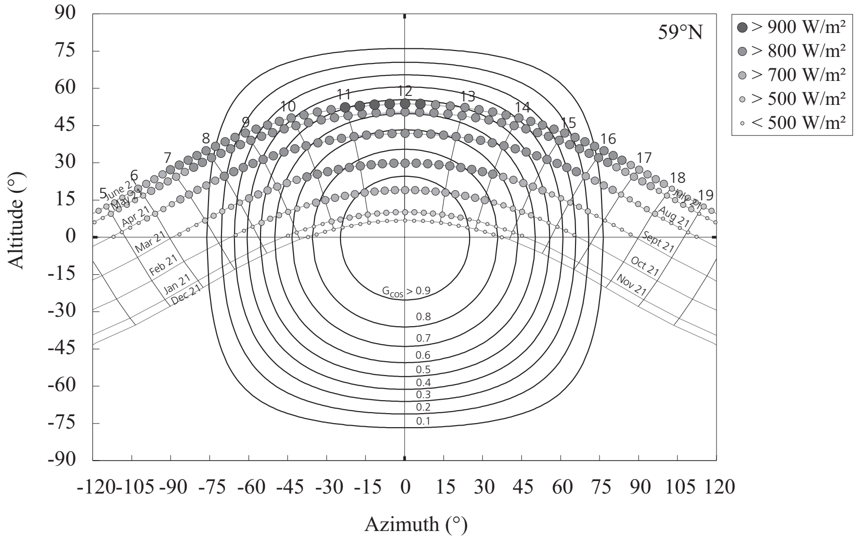


Fig. 7 Chart of the normalised Gcos-values for a vertical, south-oriented, triple pane, clear glass window superimposed on the solar path diagram for latitude 59°N showing the intensity of the direct normal solar radiation (I_{DN}) for clear days in Stockholm (W/m^2).

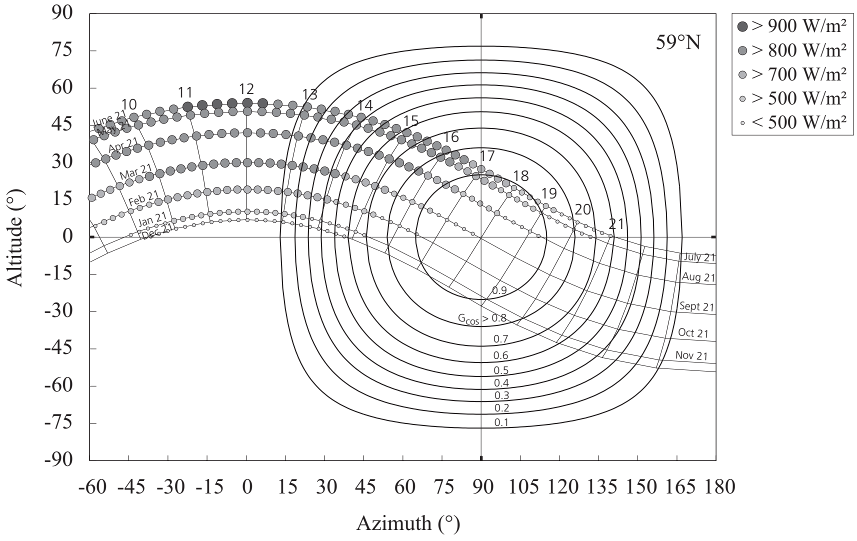


Fig. 8 Chart of the normalised Gcos-values for a vertical, west-oriented, triple pane, clear glass window superimposed on the solar path diagram for latitude 59°N showing the intensity of the direct normal solar radiation (I_{DN}) for clear days in Stockholm (W/m^2).

2.1.4 The intensity of solar radiation

The intensity of solar radiation varies throughout the day and the year. This parameter can also be included in the previous figures using points of different sizes as shown in Fig. 7-8. These figures show the relationship between the solar position (and time), the intensity of the direct normal radiation on clear days (calculated according to Brown & Isfält, 1969) and the window Gcos-values. Fig. 7 shows the correct superposition for a vertical, south-oriented, triple pane, clear glass window. Fig. 8 is for the same window oriented towards the west direction.

These charts can be used to calculate the solar gain (Q_{sol}) in the building due to direct solar radiation using:

$$Q_{sol} = I_{DN} \cdot Gcos \cdot A \qquad (5)$$

where A is the window area.

Note that since the intensity of the direct normal solar radiation is not symmetrical about the solstice, each point in Fig. 7-8 is an average of the values for two symmetrical months. A more precise approach would consist of having two charts, one for each half year.

2.2 Examples: Design of an awning

In order to show how the charts introduced in the previous sections can be used in practice, we present two specific examples where an awning must be defined for a south- and west-oriented office room in Stockholm (latitude 59.35°N, longitude 18.07°E). In these examples, the awning is to be used continuously only during the cooling season, which is from early May to the end of September according to a previous analysis of annual cooling loads for the same room (Dubois, 1999). A dark blue (85% absorpt., 1% transm.) awning with a slope of 30° with respect to the building facade is assumed for both orientations.

The following procedure was used to determine the optimum awning geometry:

Step 1	Charts were produced for the relevant latitude (59.35°N) and window type (triple pane, clear glass).
Step 2	From the charts produced in step 1, the critical solar angles were identified and some shading hypotheses were made.
Step 3	The shading device geometry was determined for each shading hypothesis identified in step 2.
Step 4	Energy simulations were carried out to determine which of the shading hypotheses defined in step 3 was optimum in terms of annual energy use.

2.2.1 Energy simulations

The energy simulation program *Derob-LTH* was used in the examples to determine which of the shading hypotheses was optimum in terms of annual energy use (step 4). *Derob-LTH,* which is an acronym for Dynamic Energy Response of Buildings, originates from the University of Texas (Arumi-Noé, 1979) but has been under continuous development at Lund University's Department of Building Science (Kvist, 1998; Källblad, 1999). The program uses hourly data for the exterior temperature and solar radiation intensity and updates the solar position four times every month. The window and shading models have the following characteristics:

- Coarse ray tracing and Fresnel calculation of the direct radiation.
- View factor and Fresnel calculation of the diffuse radiation.
- One thermal node for each pane.
- Shading device transmits and reflects diffusely.
- One thermal node approximating the thermal balance for all shading devices.
- Long wave sky radiation included.

The shading and window models in *Derob-LTH* have been validated experimentally using two full-scale guarded hot boxes exposed to the natural climate. A comparison between measured and simulated energy for a dark and a light awning has shown a maximum error of 3% with respect to the incident solar radiation (Källblad & Wallentén, 1999).

2.2.2 Office room

The Stockholm office was a 2.9-m wide by 4.2-m deep rectangular room (Fig. 9). The room had a 1.8-m wide by 1.3-m high, triple-pane, clear glass window with a U-value of 1.88 W/m^2K and a normal g-value (g_0) of 0.67.

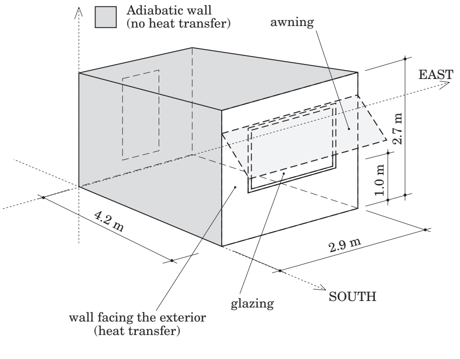


Fig. 9 Office room.

The exterior wall was a standard construction with respect to Swedish norms with a U-value of 0.18 W/m^2K. The room was assumed to be surrounded by office space at the same temperature. Thus, all “interior” walls were modelled as adiabatic surfaces. A free horizon with no obstruction and a ground reflectance of 20% were assumed.

The room had constant infiltration (0.1 ach) and ventilation (10 l/s) rates and internal heat gains from one occupant (90 W), a computer and monitor (120 W) and energy-efficient lighting (10 W/m^2). These gains were only assumed during weekdays at normal office hours (8-17). The temperature set points were 20°C (heating) or 24°C (cooling) during work hours and 18°C (heating) or 28°C (cooling) the rest of the time.

3. RESULTS

3.1 Optimum awning geometry, south orientation

The solar path diagram for Stockholm and the chart of Gcos-values for a south-oriented, triple-pane, clear glass window were produced and are shown in Fig. 7. This figure shows that September is the month with the lowest solar altitudes among the cooling months (May, June, July, August, September). It is also the month when the solar path is within a region of high Gcos-values (> 0.8) around noon when the intensity of solar radiation is high (> 800 W/m^2). For other months with high solar radiation intensity (May, June and July), the Gcos-value is never higher than 0.6, which means that the window itself reduces the intensity of the incident radiation by at least 60% (100(1-Gcos·g_0)) during these months.

While the awning’s length can be defined according to the solar altitude in September, its width will depend on the required period of shading during the day. The building is only occupied from 08.00-17.00 and this period can thus be accepted as the maximum period of shading required. Since the work hours are asymmetrical with respect to the solar path[1], and since a symmetrical awning (about the window) is assumed, 17.00 hours becomes the design hour. The minimum shading period is 11.00-13.00 hours, which falls within the region of highest Gcos-values and high solar radiation intensity.

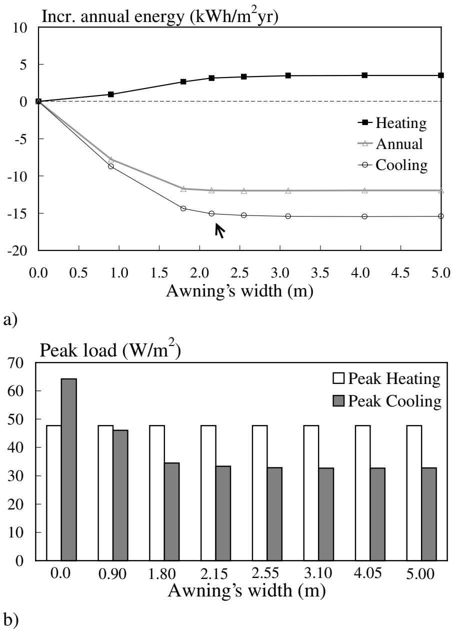
Considering the solar path and awning symmetry about the window, there are thus 5 shading schemes to be considered: 07.00-17.00, 08.00-16.00, 09.00-15.00, 10.00-14.00 and 11.00-13.00 hours. The awning’s dimensions (assuming a slope of 30°) were calculated for these 5 shading schemes and are presented in Table 1.

Table 1 shows that the definition of the shading period over one day significantly affects the size of the awning. Shading schemes 1-3 yield unrealistically wide awnings. Since the Gcos-values and the intensity of solar radiation are lower before 10.00 hours and after 14.00 hours (Fig. 7), and since partial shading will be provided even for hours falling outside each shading scheme, shading schemes 1-3 can be eliminated. The design problem then consists of choosing between two alternatives: shading schemes 4 or 5.

Table 1 Awning dimensions according to 5 shading schemes, south orientation.

Shading scheme	Shading period, Sept. 21 (hours)	Length L (m)	Width W (m)
1	07.00-17.00	1.13	6.65
2	08.00-16.00	1.12	4.05
3	09.00-15.00	1.12	3.10
4	10.00-14.00	1.12	2.55
5	11.00-13.00	1.12	2.15

The impact on energy use of the shading schemes defined using the chart was studied using energy simulations. Although only 2 schemes were proposed, a total of 8 simulations were carried out in order to show the impact of various alternatives. The awning’s length was 1.12 m for all the cases studied (from Table 1) and the width was varied from 0 to 5 m. The incremental annual energy use for cooling and heating the room as well as the annual peak heating and cooling loads are presented in Fig. 10.



a)

b)

Fig. 10 a) Incremental annual energy use (kWh/m^{2}yr) and b) peak heating and cooling loads (W/m^2) for the south-oriented office room.

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[1] In this study, daylight savings time was not used.

Fig. 10a shows that the annual cooling demand decreased almost linearly as the awning's width increased from 0 to 1.8 m. However, little additional cooling savings were obtained over 2.15 m. The curve stabilised into a straight horizontal line from this point. The same occurred with heating loads although the increase in the heating demand was not as steep as the reduction in cooling between 0 and 1.8 m.

Fig. 10b shows that the peak cooling demand was reduced by almost 50% with the 1.8-m wide awning but that no significant reductions occurred over 1.8 m. The peak heating load was unaffected by the awning's size, which is normal since the highest heating loads occur at night and outside the cooling season.

According to Fig. 10, the optimal awning dimension was thus around 2 m considering the cooling demand and annual energy use[2]. This solution corresponds to shading scheme 5, which was the one covering only the region of highest Gcos-values (> 0.8).

3.3 Optimum awning geometry, west orientation

Fig. 8 shows the correct superposition of the Gcos-values and the solar path diagram for the west orientation. This figure shows that:

1) September has the lowest solar altitudes among the overheating months;
2) the sun is within the region of highest Gcos-values at the end of the day i.e. around 17.00 hours but the intensity of solar radiation is lower at this time;
3) the period 12.00-13.00 hours can be neglected since the sun is within a region of low Gcos-values (< 0.1).

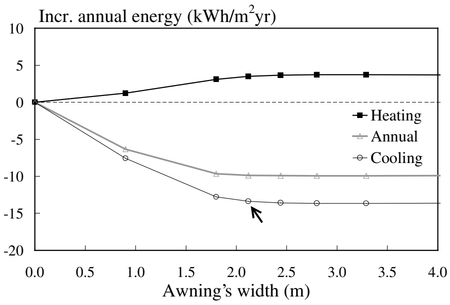
As for the south orientation, 5 shading schemes remain after the periods before 13.00 hours and after 17.00 hours are eliminated. Table 2 shows the awning dimensions for these 5 shading schemes assuming an awning's slope of 30° for all the cases. Note that the awning's length was determined according to the solar altitude at 17.00 hours while the width was determined according to the beginning of the shading period.

Table 2 Awning dimensions according to 5 shading schemes, west orientation.

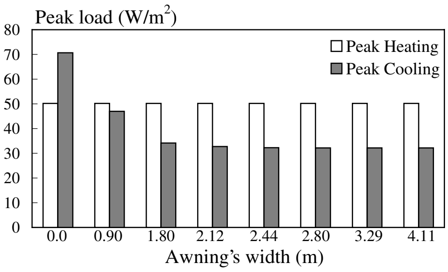
Shading scheme	Shading period, Sept. 21 (hours)	Length L (m)	Width W (m)
1	13.00-17.00	1.39	4.11
2	14.00-17.00	1.39	3.29
3	15.00-17.00	1.39	2.80
4	16.00-17.00	1.39	2.44
5	17.00-17.00	1.39	2.12

Table 2 shows that shading schemes 1-2 yield unrealistically wide awnings. Since partial shading will be provided even for hours falling outside each shading scheme and since shading schemes 1-2 cover Gcos-values lower than 0.7 (which means that the window itself will reduce the incident radiation by at least 53%), these shading schemes can be eliminated. The design problem then consists of choosing between three alternatives: shading schemes 3, 4 or 5.

The impact on energy use of these shading schemes was studied using computer simulations. The awning's length was 1.39 m (from Table 2) for all the cases and the width was varied from 0 to 4.11 m. The incremental annual energy use for cooling and heating the room as well as the annual peak heating and cooling loads are presented in Fig. 11.



a)



b)

Fig. 11 a) Incremental annual energy use (kWh/m^{2}yr) and b) peak heating and cooling loads (W/m^2) for the west-oriented office room.

Fig. 11a shows that the cooling demand decreased as the awning's width increased from 0 to 2.12 m. However, little additional cooling savings were obtained over 2.12 m. As for the south orientation, the heating loads increased linearly as the awning's width increased from 0 to 1.8 m but little change occurred over 2.12 m.

As for the south orientation, the peak cooling load (Fig 11b) was reduced by almost 50% when the awning's width increased from 0 to 1.8 m but increasing the width over 1.8 m had little effect on the peak cooling load. The

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[2] Heating and cooling loads were added up in a 1:1 ratio.

peak heating load was unaffected by an increase in the awning's width.

Fig 11 thus shows that the optimum width was around 2 m, as for the south orientation. This corresponds to shading scheme 5, which only provides complete shading at 17.00 hours. Note that it is the time when the sun is within the region of highest Gcos-values (> 0.9).

4. DISCUSSION

The example shows that the chart provides meaningful information about the window properties. This information can be used to restrict the early design hypotheses for the shading device. In this case, many shading schemes were included in the analysis although some of them covered regions with low Gcos-values. However, the energy simulations indicated that the optimum awning dimensions corresponded to the less strict shading scheme i.e. the one that only covered regions with the highest Gcos-values. This suggests that the initial shading hypotheses could have been even more restrictive.

It was shown that relatively narrow awnings (~ 2 m) could provide efficient shading both for a south- and a west-oriented office in Stockholm. This indicates that solar radiation coming from the sides of the awning has a relatively negligible importance with respect to annual energy use. The most important is to shade the window when the sun is within a region of high Gcos-values i.e. around the window normal.

However, since narrow awnings will let the direct radiation hit the window at certain hours, it is essential to provide the building occupant with an extra shading device like a curtain, an interior screen or a venetian blind. A shading device will in any case be necessary during the winter to avoid glare problems. This extra shading device should be manually adjustable and preferably located on the interior side of the window. Interior shading devices have a poor shading coefficient, which means that they will only affect the solar heat gains in a negligible way during the heating season. Littlefair (1999) also suggested to use a hybrid approach—with an exterior device to control summer heat and internal blinds for glare—in buildings where both heat and glare control are important. He observed that while external shading systems are very efficient at preventing overheating, only sophisticated external louver systems are really effective at controlling both solar gains and sun glare.

5. CONCLUSIONS

A simple chart to define the optimum geometry of shading devices was presented. The chart, which is complementary to Mazria's (1979) solar path diagram, provides additional information about the window solar angle dependent properties and the window's geometrical relationship to the sun beam. This additional information allows to identify the periods when solar radiation is most likely to cause overheating in the building

The main advantage of the proposed chart is its simplicity. One figure shows the relationship between the solar position, the intensity of the direct normal radiation and the window angular properties.

Another advantage of the chart is its generality. For a given window type, the shape of the overlay describing the window properties (Gcos-values) is the same for any orientation or latitude.

Two examples were provided where the chart was used to define the geometry of an awning installed on a south- and west-oriented office room in Stockholm. The dimensions of the awning obtained using the chart and further specified with the energy simulations were small compared to the ones obtained if we had only considered the incident sun and the hours of occupation of the building. Such an approach yielded an awning three times wider than necessary on the south facade and double as wide as necessary on the west facade.

This study shows that, even at an early design stage and with simple tools, it is possible to define the optimum geometry of a shading device quite accurately just by considering the window properties. This will permit to restrict the number of iterations in the computer simulations used at a later stage in the design process. When computer simulations are not available, the proposed method will avoid oversizing shading devices, which is not economical, reduces daylighting and blocks a larger portion of the window view.

The proposed chart is solely based on considerations of energy use for heating and cooling buildings. In a real context, it is paramount to also consider the relationship between the shading device, daylighting and visual comfort.

ACKNOWLEDGEMENTS

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Article III

The Design of Seasonal Awnings for Low Cooling and Heating Loads in Offices

Marie-Claude Dubois, M. Arch., Tech. Lic.[*]

1. INTRODUCTION

In cold climates, exterior shading devices can provide larger annual energy savings than tinted and reflective glass since they can be used seasonally thus allowing for a passive utilisation of solar gains during the winter (Dubois 1998). Awnings and similar types of shading devices are of particular interest because they have a low shading coefficient since 1) they reject solar energy before it reaches the building and 2) most of the heat absorbed in the shade is convected to the outdoor air. Awnings also leave some part of the window view unobstructed, which is positive both in terms of occupant satisfaction and daylighting availability. However, awnings are particularly susceptible to mechanical failure and wind damage. Another problem is that little is known about the relationships between energy use and an awning's geometry and attributes such as colour (absorptance, reflectance) and transmittance. In an attempt to elucidate these complex relationships, a parametric study of energy use for heating and cooling an office room located in Stockholm was initiated as part of a large project on solar shading devices at Lund Institute of Technology (Wall & Wallentén 1999).

2. METHOD

2.1 Computer program

The dynamic calculation program DEROB-LTH (Arumi-Noé 1979; Källblad 1999) was used to predict the energy performance of the office room. DEROB-LTH uses a geometrical description of the building where direct and diffuse solar radiation is distributed to various surfaces in the space. The program has recently been supplemented with advanced algorithms for windows and exterior shades (Källblad 1999). The new shading algorithm calculates the impact of shades on both direct and diffuse solar radiation at each hour assuming that all radiation incident on the shade is transmitted or reflected as pure diffuse radiation. The impact of

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the shade's temperature on thermal radiation exchanges to the window is also taken into account using a simplified calculation method (Wall & Wallentén 1999). This new shading module has been validated experimentally using two full-scale guarded hot boxes exposed to the natural climate. It was found that the program predicts the primary and total solar transmittance through the window-shade system very accurately and that heating and cooling loads are predicted with a maximum error of 10% with respect to the experiment (Wall & Wallentén 1999).

2.2 Office room

The south-orientated office room modeled in DEROB-LTH was a 2.9-m wide, 4.2-m deep and 2.7-m high (interior dimension) rectangular space (Fig. 1). The triple-pane, clear glass window, which measured 1.8 m (width) by 1.3 m (height), had a U-value of 1.88 W/m^{2}K and a shading coefficient of 0.76. A 0.1-m wide frame with a 0.1-m recess with respect to the glazing was assumed. The exterior wall was a standard construction with respect to Swedish norms with a U-value of 0.18 W/m^{2}K. The room was assumed to be surrounded by office space at the same temperature. Thus, all "interior" walls were modeled as adiabatic surfaces. A free horizon with no obstruction and a ground reflectance of 20% were assumed.

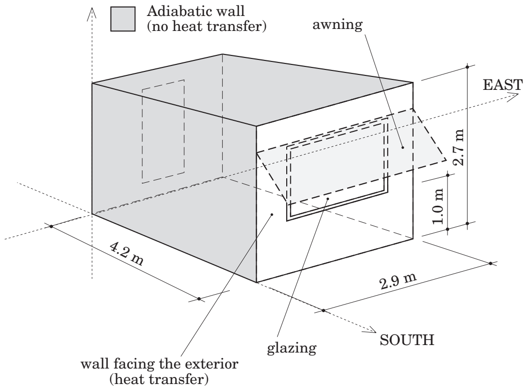


Figure 1 Office room.

The room had constant infiltration (0.1 ach) and ventilation (10 L/s) rates and internal heat gains from one occupant (90 W), a computer and monitor (120 W) and energy-efficient lighting (10 W/m^2). These gains were only assumed during weekdays and normal office hours

(8-17). The temperature set points were 20°C (heating) or 24°C (cooling) during work hours (8-17) and 18°C (heating) or 28°C (cooling) the rest of the time and during weekends.

2.3 Base case awning

Initially, a dark blue awning with an arbitrary slope (θ= 30°) was built in the model. The awning's geometry was determined so that the window would be completely shaded during the "typical" cooling season i.e. from May 1st to September 30th for incidence angles comprised within an angle of 120° with respect to the glazing surface (in all directions) (Fig. 2). The glazing transmittance drops dramatically beyond this angle making it unnecessary to provide additional shading to the window. Note also that, during the cooling season, the sun's azimuth was within the 120° angle during most work hours. The initial awning's length (*L*) and width (*W*) were determined as a function of the lowest solar altitude (α) within the 120° angle during the May-September period using the following relationships (see appendix):

$$L = \frac{1.3 \cdot \cos 60°}{\left[(\tan\theta \cdot \tan\alpha) + \cos 60°\right]\cos\theta} \tag{1}$$

$$W = 2(L \cdot \sin\theta \cdot \tan 60°) + 1.8 \tag{2}$$

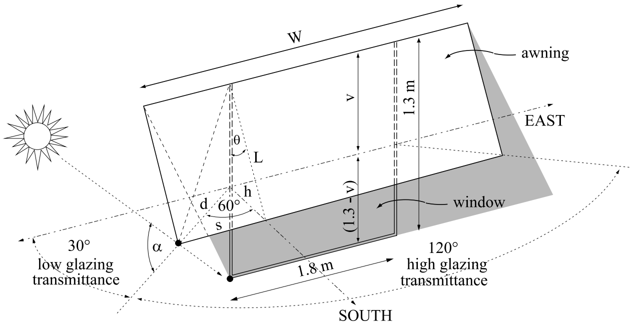


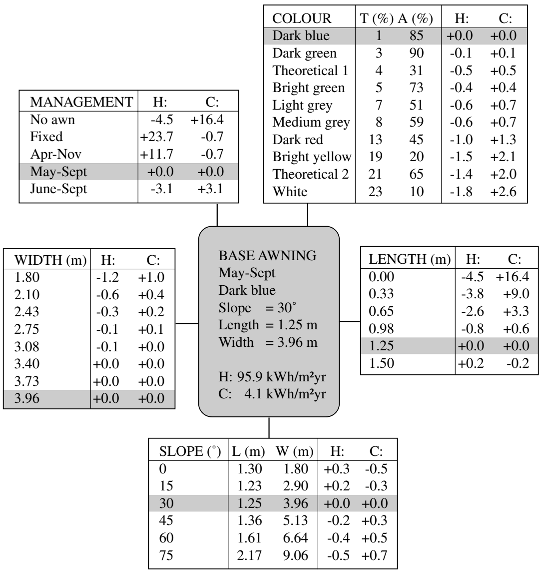
Figure 2 Determination of the base case awning length (*L*) and width (*W*).

3. RESULTS

The plan of the parametric study and the results obtained are presented in Figure 3.

3.1 Seasonal Management Strategy

Keeping the base case attributes constant, the seasonal management strategy was varied so that the awning was installed from the first to the last cooling day (Apr-Nov) and



MANAGEMENT	H:	C:
No awn	-4.5	+16.4
Fixed	+23.7	-0.7
Apr-Nov	+11.7	-0.7
May-Sept	+0.0	+0.0
June-Sept	-3.1	+3.1

COLOUR	T (%)	A (%)	H:	C:
Dark blue	1	85	+0.0	+0.0
Dark green	3	90	-0.1	+0.1
Theoretical 1	4	31	-0.5	+0.5
Bright green	5	73	-0.4	+0.4
Light grey	7	51	-0.6	+0.7
Medium grey	8	59	-0.6	+0.7
Dark red	13	45	-1.0	+1.3
Bright yellow	19	20	-1.5	+2.1
Theoretical 2	21	65	-1.4	+2.0
White	23	10	-1.8	+2.6

WIDTH (m)	H:	C:
1.80	-1.2	+1.0
2.10	-0.6	+0.4
2.43	-0.3	+0.2
2.75	-0.1	+0.1
3.08	-0.1	+0.0
3.40	+0.0	+0.0
3.73	+0.0	+0.0
3.96	+0.0	+0.0

BASE AWNING
May-Sept
Dark blue
Slope = 30°
Length = 1.25 m
Width = 3.96 m

H: 95.9 kWh/m²yr
C: 4.1 kWh/m²yr

LENGTH (m)	H:	C:
0.00	-4.5	+16.4
0.33	-3.8	+9.0
0.65	-2.6	+3.3
0.98	-0.8	+0.6
1.25	+0.0	+0.0
1.50	+0.2	-0.2

SLOPE (°)	L (m)	W (m)	H:	C:
0	1.30	1.80	+0.3	-0.5
15	1.23	2.90	+0.2	-0.3
30	1.25	3.96	+0.0	+0.0
45	1.36	5.13	-0.2	+0.3
60	1.61	6.64	-0.4	+0.5
75	2.17	9.06	-0.5	+0.7

Figure 3 Plan of the parametric study and incremental heating (H:) and cooling (C:) loads (kWh/m^2yr) with respect to the base case awning. (Negative values mean that energy was saved). Heating and cooling loads are presented in a 1:1 ratio.

from the last to the first heating day (June-Sept) of the year. Figure 4a shows that the seasonal schedule had a large impact on both annual energy use and peak loads for cooling.

The use of a seasonal awning reduced annual cooling by up to 17.1 kWh/m^2yr (80%) while using an awning year-round (Fixed) increased heating by 28.1 kWh/m^2yr (31%) compared to a case without awning (No awn). Figure 4a also shows that the use of a seasonal awning had a large impact on the cooling peak load, which was reduced by up to 35 W/m^2 (55%), and no impact on heating peak loads (occurred at night). Overall, the May-Sept schedule was optimal: it yielded one of the lowest annual heating and cooling loads combined with the lowest peak cooling load.

3.2 Colour

It was found that the annual energy use varied mainly as a function of the awning's transmittance. Increasing the transmittance from 1-23% yielded a reduction in annual heating loads by 1.8 kWh/m^2yr (1.9%) and an increase in cooling by 2.6 kWh/m^2yr (63%) (Fig. 4b). Note that although this relative increase in cooling seems large, the absolute additional load was marginal compared to the total annual energy use for the base case (100 kWh/m^{2}yr). Since the transmittance had a larger impact on cooling than on heating loads, dark-coloured awnings (low transmittance) yielded a lower annual energy use than light-coloured ones. However, it should be noted that the optimal solution depends on the relative efficiency of the cooling and heating systems. (In this study, the space loads were not adjusted to a specific system's efficiency i.e. heating and cooling loads are in a 1:1 ratio). Note also that increasing the transmittance affected cooling peak loads moderately (+7 W/m^2, 23%) and had no effect on peak heating loads.

3.3 Width

Figure 4c shows that a reduction in the awning's width from 3.96 m (base case) to 1.8 m (window width) yielded a reduction in annual heating by 1.2 kWh/m^{2}yr (1%) and an increase in cooling by 1 kWh/m^{2}yr (24%). Most of the impact of the width was between 1.8 m and 2.4 m and, thus, negligible additional cooling savings were obtained with awnings larger than 2.4 m (0.3 m on each side of the window). Note also that the awning's width had a negligible impact on peak cooling loads and no impact on peak heating loads.

3.4 Length

Figure 4d shows that a reduction in the awning's length from 1.25 m (base case) to 0.33 m (25% of the base case) more than tripled the cooling demand (+9.0 kWh/m^{2}yr) and reduced the heating demand by 3.8 kWh/m^{2}yr (4 %). The length thus generally had a larger impact on the cooling than on the heating demand. Note also that above 0.9 m, the awning's length had a negligible impact on annual energy use. Figure 4d also shows that the awning's length had a large impact on the peak cooling load, which was reduced by around 32 W/m^2 (52%) through an increase in length from 0-1.5 m.

3.5 Slope

In order to study the impact of the slope on diffuse and reflected radiation (from the backside of the awning), the awning's length and width were adjusted for each slope angle studied so that an equivalent shade from direct radiation was produced on the window. Figure 4e shows that increasing the awning's slope from 0-75° reduced the annual heating demand by 0.8 kWh/m^{2}yr (0.8%) and increased the annual cooling demand by 1.2 kWh/m^{2}yr (33%).

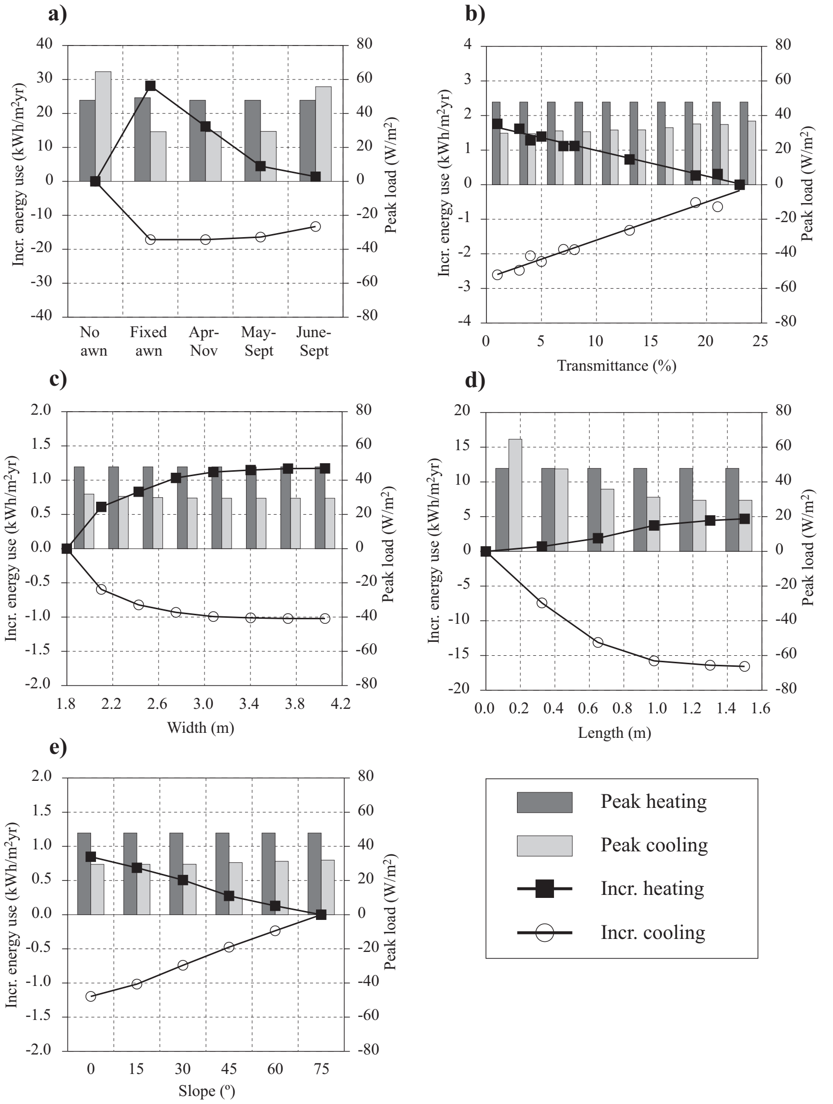


Figure 4 Incremental annual energy use (kWh/m^{2}yr) and peak loads (W/m^2) for heating and cooling as a function of a) the seasonal management strategy, b) the transmittance, c) the width, d) the length and e) the slope. Annual and peak heating and cooling loads are presented in a 1:1 ratio.

The relationship between the slope and the annual heating and cooling loads was roughly linear and the slope generally had a larger impact on cooling than on heating loads. Steeper slopes (0-30°) yielded a lower annual cooling demand resulting in a lower annual energy use than shallow slopes. Overall, the impact of the slope on peak loads was negligible.

4. DISCUSSION AND CONCLUSIONS

A parametric study of energy use for heating and cooling an office room equipped with a seasonal awning was presented. The study indicated that the seasonal management strategy and the awning's length were factors affecting energy use and peak cooling loads in a significant way. The large impact of the seasonal management strategy suggests that larger energy savings could be obtained with dynamic shades that constantly adjust to environmental conditions. A variation of the awning's colour also indicated that the annual energy use varies as a function of the transmittance of the awning's fabric. Overall, this property had a moderate impact on annual energy use and peak cooling loads and it was found that darker awnings yielded a lower annual cooling demand because dark-coloured fabrics have a lower transmittance than light-coloured ones. This finding suggests that opaque awnings should yield lower cooling loads. Finally, the study indicated that the awning's width and slope had a relatively small impact on annual energy use and a negligible impact on peak loads. It was found that over a certain width, little additional cooling savings were obtained suggesting that awnings should be slightly larger than the window but that extremely large awnings are a waste of material.

Overall, the results obtained for the width and the length generally indicate that the base case awning was oversized. There is a possible relationship between the total awning area (width and length) and energy use that has not been thoroughly investigated here. However, it should be noted that a simulation (not presented) with reduced awning dimensions ($L = 0.9$ m; $W = 2.1$ m) yielded results similar to the ones obtained for the base case (-1.4 kWh/m^{2}yr for heating; +1.3 kWh/m^{2}yr for cooling). Note that there are clear advantages to reducing the awning's dimensions such as a reduction of production costs, an improvement of the view out from the interior, and an increase in daylighting availability in the space, which can provide additional energy savings for lights and cooling.

Finally, it should be mentioned that the conclusions of this study are solely drawn from results of computer simulations. Although the computer program used (DEROB-LTH) has been validated experimentally and it has been shown (Wall & Wallentén 1999) that it predicts heating and cooling loads with a maximum error of 10%, investigations and measurements in real buildings should be made to confirm the findings described in this paper.

5. APPENDIX

Equations (1) and (2) were derived from the following equations:

$$L = v(\cos\theta)^{-1} \quad (3)$$

$$v = 1.3 - d\tan\alpha \quad (4)$$

$$d = h(\cos 60°)^{-1} \quad (5)$$

$$h = L\sin\theta \quad (6)$$

$$s = L\sin\theta\tan 60° \quad (7)$$

L is the awning's length (m); v and h are respectively the vertical and horizontal projection of the awning (m); θ is the awning's slope (°); d is the horizontal projection of the distance between the awning's lower corner and its shadow on the vertical wall (m); α is the lowest solar altitude for the period considered (°); and s is the awning's width exceeding the window width on each side (m) (Fig. 2).

6. ACKOWLEDGEMENT

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Article IV

AWNINGS AND SOLAR-PROTECTIVE GLAZING FOR EFFICIENT ENERGY USE IN COLD CLIMATES

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ABSTRACT

Annual energy use for heating and cooling of a single-occupant office room located in Lund (Sweden) was analysed for eight solar-protective glazing options and one shading system. Various glazing-to-wall area ratios (GWAR) and orientations were studied. The energy performance was assessed through computer simulations with the program *DEROB-LTH* recently supplemented with improved algorithms for windows and exterior shading systems. The study showed that the most energy-efficient glazing option was orientation-dependent: south and north orientations required higher solar transmittance or GWAR than east and west, assuming similar coefficients of performance (COP) for heating and cooling systems and equivalent thermal losses among all cases. The study also demonstrated that a removable awning coupled with clear glazing performed better in terms of annual energy use than all solar-protective glazing options tested. However, it was also demonstrated that the fixed awning resulted in higher annual energy use compared with solar-protective glazing for all orientations. This study generally shows that glazing and shading strategies should be flexible in cold climates and allow the use of solar gains during the heating season while limiting those gains during the cooling season. Removable or dynamic shading systems offer larger potential energy savings than fixed systems or solar-protective glazing.

1 INTRODUCTION

In spite of developments in the area of switchable glazing technologies, there is still an interest to study shading devices and their impact on building energy use because shading systems represent a great retrofit opportunity at relatively low investment costs. In addition, most shading devices have the advantage over low solar transmittance or electrochromic glazing to leave the view to the exterior almost unchanged even when direct solar radiation is completely blocked. Shading can also provide additional insulation to the windowpanes. Most importantly, shading systems are already commonly used in buildings, even in cold climates, because they allow the control of solar gains, daylighting levels and privacy. Thus, the impact of shading systems on energy use in buildings must be assessed to develop energy-efficient strategies, to identify bad shading practices yielding a wastage of energy and to compare the energy savings accomplished with shading systems with the ones obtained with advanced glazing technologies available today.

Studies of the impact of shading on annual energy use have shown that shading reduces cooling loads substantially, thus reducing annual energy use in a building. However, most of these studies have been aimed at warm climates [3]. Little work has been done to assess the impact of shading devices on annual energy use in heating-dominated climates. One study [5] showed that exterior shading devices and absorbing glass are net energy losers in heating-dominated climates and that interior devices perform better than exterior fixed devices because they shade the entire window while providing additional insulation to the windowpanes. Another study [14] demonstrated that window films provide no savings at all in heating-dominated climates. A third study [13] showed that an energy-efficient shading strategy is climate dependent: in cooling-dominated climates, lower annual energy use is obtained with lower shading coefficients (better shade) while heating-dominated climates require higher shading coefficients. However, these studies were achieved through computer simulations using a shading coefficient based approach. This approach is no longer valid with dynamic energy calculation models. For energy analyses including hourly building performance calculations, angular dependent values of the solar heat gain coefficient should be used instead [8, 10].

In this research, the impact of one awning and of solar-protective (reflective, absorbing) and low-emissivity coated glazing on heating and cooling loads is analysed for one office room located in Lund (southern Sweden). Eight glazing options and three shading strategies are studied. The glazing-to-wall area ratio (GWAR) is varied 0-70% and the office room is alternatively orientated N, NE, E, SE, S, SW, W and NW.

2 METHOD

2.1 Computer simulations

2.1.1 Energy performance

The building energy performance was assessed with the dynamic program *DEROB-LTH* developed at the University of Texas [2]. This program has been constantly improved at Lund University's Department of Building Science, Lund, Sweden. It runs on a PC in the MS Windows environment [6]. The program was recently provided with an improved window module that treats the window in the same way, generally, as the program *WINDOW 4.1* [1]. *DEROB-LTH* was also recently supplemented with an algorithm that calculates the effect of exterior shades like awnings on direct and diffuse solar radiation at each hour interval. This new algorithm assumes that all direct and diffuse radiation reaching the exterior shade is either reflected or transmitted as pure diffuse radiation [7].

2.1.2 Windows thermal-optical properties

The program *WINDOW 4.1* was used to calculate the windows' thermal and optical properties (at 10^{o} increments). The solar angle dependent optical properties were calculated from a manufacturer's measurements for normal incidence. *WINDOW 4.1* gives accurate angular properties for homogeneous glasses (uncoated) by applying Fresnel equations and Snell's law [4]. This procedure is valid for most clear, low-iron and absorbing glasses but may induce inaccuracies for coated glazing as in the case of reflective and low-emissivity coated glass tested in this study. A recent study [11], however, indicates that these inaccuracies are within a few percent.

2.2 Constant parameters

2.2.1 Office module

The office module was a 4.2 m deep, 2.9 m wide and 2.7 m high (floor to ceiling) single-occupant room (Fig. 1). The room was constructed according to ordinary building practices for commercial offices in Sweden. Heat transfer through the room's walls, floor and ceiling were, however, selectively constrained in order to isolate the energy effects due to the window and/or shade system solar properties. The room's floor, ceiling and all walls except the wall facing the "exterior" were thus wrapped in a thick insulation layer to make all walls adiabiatic (i.e. having no heat transfer). The insulation thickness in the wall facing the "exterior" (surrounding the window) was adjusted to yield equivalent thermal losses through the window-wall system for all cases studied. This procedure made it possible to compare windows with different thermal properties (U-value).

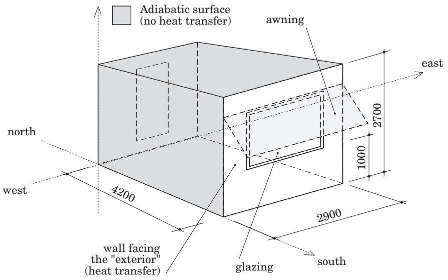

Figure 1: Office module.

2.2.2 Internal loads, heating and cooling thermostat settings, ventilation and infiltration rates

The internal loads in the office room consisted of the heat generated by the occupant (90 W), a computer and monitor (120 W) and energy-efficient lighting (120 W). No daylighting utilisation (dimming system) was assumed. The thermostat settings for heating were 20ºC during working hours (8-17), with a night setback temperature of 18ºC. For cooling, the thermostat settings were 24ºC (8-17), with a night setback of 28ºC. The ventilation rate was 10 l/s and the infiltration was 0.1 ach. No heat recovery of exhaust air was assumed.

2.2.3 Climate

The office room was located in Lund in the south of Sweden (latitude 55.72 N). The climate file used was for 1988, which is considered a normal year [15]. During that year, the average annual temperature was 8.2ºC, the average minimum temperature was 0.4ºC and the average maximum temperature was 16.7 ºC. The average global solar radiation was 108 W/m^2 on a horizontal surface and 85 W/m^2 on a vertical surface (south) [15].

2.3 Variables

2.3.1 Glazing types

The glazing types were chosen to represent a wide range of solar transmittance values. The glazing options studied are presented in Table 1 below.

Table 1: Glazing types.

	Glazing types	SC	$Tsol_{\perp}$ (%)	$U\text{-value}_{COG}$ (W/m^2K)
A	D-reflective bronze*	0.16	5	2.06
B	D-reflective blue	0.32	18	2.62
C	T-reflective “reflecta”	0.44	30	1.87
D	T-absorbing blue	0.48	31	1.87
E	D-absorbing blue*	0.56	38	2.63
F	T-low-emissivity*	0.60	41	0.93
G	T-clear	0.76	56	1.88
H	D-clear*	0.86	68	2.65

D = double pane; T = triple pane
** = with argon (others are with air)*

2.3.2 Shading system

A dark blue awning with absorptance 67% and transmittance 7% was designed so that it would block all direct solar radiation on the south façade during the cooling season (May-September) (Fig. 1). The same awning was applied to all other façades in spite of different sun angles because it is practically impossible to shade the whole window with the type of awning used on east, west and north façades. This problem, which shows that shading systems should be chosen according to orientation, was pointed out by numerous authors [9, 12].

Three shading strategies were used: a fixed awning, an awning installed only during the cooling season (May-1 to September-30), and a “dynamic” awning. The “dynamic” awning was drawn up completely on heating days and fully extended to its lowest point on cooling days. *DEROB-LTH* does not yet allow the modelling of a dynamic awning so annual energy use for this case was calculated separately on a calculation spreadsheet.

2.3.3 Other variables

The other variables were the orientation and the glazing-to-wall area ratio (GWAR). The orientation was varied by 45° increments (N, NE, E, SE, S, SW, W and NW) and the GWAR was varied from 0 to 70% as shown on Figure 2.

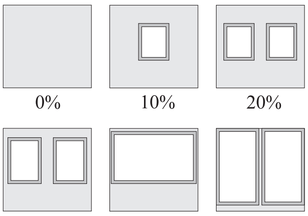

Figure 2: Glazing-to-wall area ratios (GWAR).

2.4 Simulation scheme

Three series of simulations were performed. In the first series (Fig. 3, top), the glazing type and orientation were varied for 30% GWAR. In the second series (Fig. 3, middle), the GWAR was varied for north, east and south orientations and for five glazing types. In the third series, the awning was added to glazing type H for 30% GWAR on north, east and south façades. Three shading strategies were tested (Fig. 3, bottom).

Glazing =		A	B	C	D	E	F	G	H
30% GWAR	Orientations	N NE E SE S SW W NW							

GWAR		0%	10%	20%	30%	50%	70%
Glazing	A	no glazing N E S	N E S	N E S	done for all orientations	*	*
	C		N E S	N E S		N E S	*
	D		N E S	N E S		N E S	*
	F		N E S	N E S		N E S	N E S
	H		N E S	N E S		*	*

Shading System =	Fixed awning	Seasonal awning	Dynamic awning
30% GWAR Glazing type H	N E S	N E S	N E S
	N E S	N E S	N E S
	N E S	N E S	N E S

*Thermal losses through the glazing larger than thermal losses through the window-wall system

Figure 3: Simulation scheme.

3 RESULTS AND DISCUSSION

3.1 Variation of the glazing type and orientation

In the first series of simulations, energy use was analysed for the office room with 30% GWAR, for eight glazing types and eight orientations. Results showed that low solar transmittance glazing (type A) yielded the lowest annual cooling load and the highest annual heating load. High transmittance glazing (types G, H) exhibited opposite trends. Results also indicate that the south facing room had the lowest annual heating load while the north facing room had the highest. For cooling, the southeast orientation yielded the highest annual cooling load while north yielded the lowest. East and west orientations yielded similar loads both for heating and cooling.

In absolute values, heating was more affected by a change in orientation than cooling. This is clearly shown in Figure 4: the maximal reduction in heating load due to a change in orientation was about 23 kWh/m^{2}yr while it was only 15 kWh/m^{2}yr for cooling. In percent, however, cooling was reduced by up to 58% while heating was reduced by up to 23%. The absolute maximal reduction in heating load due to a change in glazing type was about 29 kWh/m^{2}yr while, for cooling, it was about 22 kWh/m^{2}yr. In percent, cooling was reduced by at most 86% while heating was reduced by at most 27%. The glazing type was thus a more significant factor affecting energy use than the orientation, especially with respect to cooling loads.

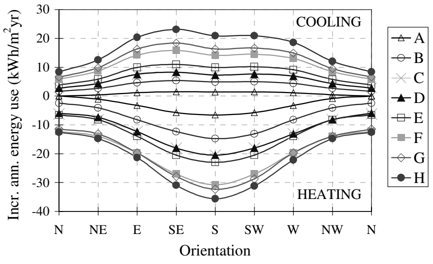

Figure 4: Incremental annual energy use (kWh/m^{2}yr) for eight glazing types and eight orientations, GWAR = 30%, in Lund.

Assuming that the heating and cooling systems had a similar COP and that energy distribution systems required the same amount of energy both for heating and cooling, heating and cooling loads were added up for the analysis of annual energy use as a function of orientation and glazing type. As shown in Figure 5, the optimal glazing strategy was orientation-dependent: on south and north façades, higher transmittance glazing (types F, G, H) yielded lower annual energy use while on east and west façades, average transmittance glazing (types C, D) performed better. Surprisingly, the low-emissivity coated glazing (type F) always yielded the lowest annual energy use for all orientations while the low solar transmittance glazing (type A) almost always yielded the highest annual energy use. Note that since thermal losses are constant for all cases, the performance of the low-emissivity coated glazing cannot be attributed to its thermal behaviour.

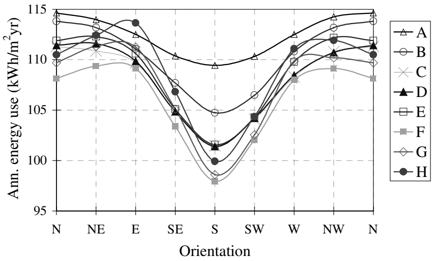

Figure 5: Annual energy use (kWh/m^{2}yr) for eight glazing types and eight orientations, GWAR = 30%, in Lund.

3.2 Variation of the GWAR, glazing type and orientation

In the second series of simulations, the GWAR was varied for north, east and south orientations and glazing types A, C, D, F and H. Results of these simulations indicated that the cooling load increased with increasing solar aperture[1] (SA). The opposite trend was observed for heating loads (Fig. 6). In general, the south orientation was more affected by a change in SA than other orientations. A significant feature of Figure 6 is that for east and south orientations, the cooling load increased in a similar way with an increase in SA. For south, however, the heating load decreased much more with increasing SA than for east. In other words, for the east orientation, increasing the SA (SC or GWAR) yielded increases in cooling loads larger than the reductions in heating load. This was especially true for SA larger than 0.3. This finding indicates that the optimal SA (hence the glazing SC or GWAR) on east (and west) orientations is determined by cooling rather than heating loads for large SA.

Assuming, again, equivalent COP for heating and cooling systems, annual energy use was analysed as a function of SA. It was found that for south, the annual energy use was minimised at SA around 0.2 while for east, annual energy use was minimised at lower SA e. g. approximately 0.12. This means that, for the south orientation, high solar

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[1] The solar aperture is the product of the SC and GWAR.

transmittance glazing (type H) yielded minimal annual energy use with GWAR around 20% while glazing type F was optimal with GWAR around 30% and glazing types C and D were optimal with GWAR around 40%. On the east façade, high solar transmittance glazing (type H) yielded lower annual energy use with GWAR around 15% while average transmittance glazing (types C, D) and glazing type F yielded lower annual energy use with GWAR around 20-30%. For the north orientation, the flat horizontal curve shown in Figure 7 indicates that the impact of the SC or GWAR on annual energy use was small. In general, the results indicate that annual energy use was minimised at lower GWAR or SC on east (and west) façades than on the south façade.

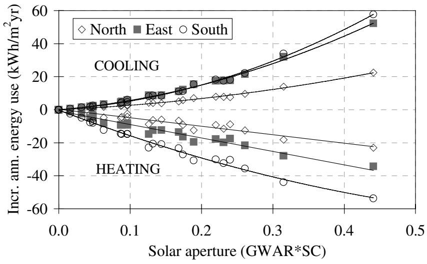


Figure 6: Incremental annual energy use (kWh/m^{2}yr) as a function of solar aperture for three orientations, in Lund.

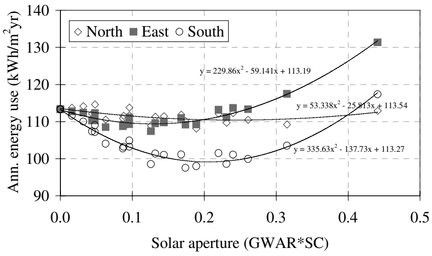
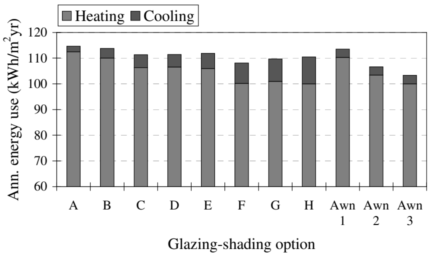


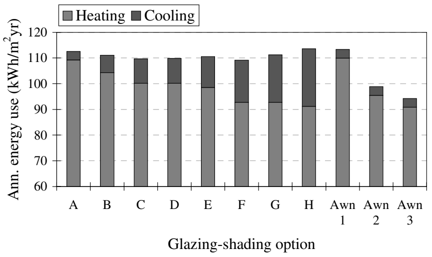
Figure 7: Annual energy use (kWh/m^{2}yr) as a function of solar aperture for three orientations, in Lund.

3.3 Introduction of a shading system

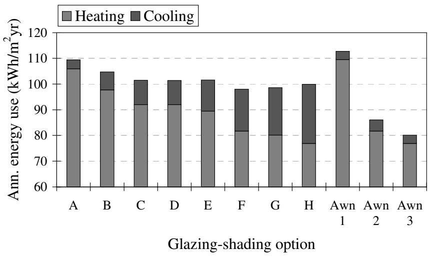
In the last series of simulations, an awning was added to the high solar transmittance glazing (type H) with 30% GWAR for three orientations and three shading strategies. Results of these simulations indicate that the fixed awning resulted in increased annual energy use due to increased heating loads for all orientations (Fig. 8). These results agree with results found by Hunn et al. [5] and Treado et al. [13, 14].



a) north



b) east



c) south

Figure 8: Annual energy use (kWh/m^{2}yr) as a function of glazing-shading option for a) north, b) east, c) south and GWAR = 30%, in Lund (Awn 1 = fixed, Awn 2 = seasonal, Awn 3 = dynamic).

The study also showed that the seasonal and "dynamic" awnings reduced the annual energy use significantly, especially on the south façade. The seasonal awning reduced the cooling load by 18.8 kWh/m^{2}yr (81%) and increased heating loads by 4.8 kWh/m^{2}yr (6%), decreasing annual energy use by 13.9 kWh/m^{2}yr (14%) compared with the clear glazing option (type H), which was one of the best glazing strategies for the south façade. The "dynamic" awning performed even better with an annual energy use reduction of 19.8 kWh/m^{2}yr (20%) compared with glazing type H.

For north and east orientations, the seasonal and "dynamic" awnings also resulted in lower annual energy use although savings were smaller than for south. Even on the north façade, the seasonal awning resulted in annual energy savings compared with all solar-protective glazing options tested. Since this façade is in the shade most of the time, the savings achieved can be attributed to the reduction in diffuse solar radiation reaching the window.

4 CONCLUSIONS

In this study, optimal transmittance properties for glazing in a heating-dominated city were identified by varying the glazing type, the GWAR and the orientation. One significant finding is that the most energy-efficient glazing option is orientation-dependent: south and north façades require higher solar transmittance or higher SA (GWAR or SC) than east and west façades. This conclusion is drawn assuming equivalent COP for cooling and heating systems and constant thermal losses among all cases. Another important finding is that a high solar transmittance glazing combined with a removable awning, either on a seasonal or on a daily basis, results in lower annual energy use than all solar-protective glazing options tested for any orientation, including north. These results are promising since the impact of the glazing-shading strategy on electricity use for lighting was not assessed. The potential to replace artificial lighting by daylighting is much higher with high than with low solar transmittance glazing. The clear glazing plus removable awning option may thus result in much larger overall energy savings than those reported here.

Although a detailed calculation method was used to obtain heating and cooling loads, the window module and shading algorithm recently implemented in *DEROB-LTH* have not been fully validated yet. Measurement work is on the way at Lund University's Department of Building Science for validation of the computer program. Future plans also include the implementation of dynamic algorithms for other types of shading devices like venetian blinds, roller shades, screens, etc. These algorithms will allow an extended study of energy patterns with different kinds of shading systems and strategies in cold climates.

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Article V

Parasol-LTH: A User-friendly Computer Tool to Predict the Energy Performance of Shading Devices

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Hasse Kvist, M. Sc., Tech. Lic.
Marie-Claude Dubois, M. Sc. in Architecture, Tech. Lic.*

1. INTRODUCTION

The shading of windows can significantly affect energy use for cooling, heating and lighting a building. Dubois (1999) found that a seasonal awning could reduce the annual cooling demand of a south-oriented office room by up to 80% in Stockholm (Sweden). Such an impact on energy use needs to be taken into consideration during the design of the building since it will affect the size and cost of the installations and could justify investing in energy-efficient shading devices. One problem is that few of the computer models that handle the complex physical interactions between the direct and diffuse sky radiation, the shade and the window have been validated experimentally (Dubois, 1997). Another problem is that most of these models are too complex to be used in conventional architectural or engineering practices. In order to overcome these limits, a computer tool called *Parasol-LTH* has been developed at Lund University as part of a large project on solar shading (Wallentén & Wall, 1999) achieved in collaboration with Nordic shading manufacturers. *Parasol-LTH* is a user-friendly interface to the energy simulation program *Derob-LTH*, which has been validated experimentally (Källblad & Wallentén in Wall & Fredlund, 1999). This paper briefly describes the computer model *Derob-LTH,* its experimental validation and the user-friendly interface, *Parasol-LTH*. An example of an application of the computer tool in a study of seasonal awnings is also presented.

2. COMPUTER MODELS

2.1 Derob-LTH

Derob-LTH, which is an acronym for Dynamic Energy Response of Buildings, originates from the University of Texas (Arumi-Noé, 1979) and has been under continuous development at Lund University's Department of Building Science (Källblad 1999, 1998). The program uses

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hourly data for the exterior temperature and the solar radiation intensity and updates the hourly solar position four times every month. The window and shading model has the following main characteristics:

- Coarse ray tracing and Fresnel calculation of the direct radiation.
- View factor and Fresnel calculation of the diffuse radiation.
- One thermal node for each pane.
- Shading device transmits and reflects diffusely.
- One thermal node approximating the thermal balance for all shadings.
- Long wave sky radiation included.

2.2 Experimental validation

The shading and window models in *Derob-LTH* have been validated experimentally using two full-scale guarded hot boxes exposed to the natural climate (Wallentén & Håkansson in Wall & Fredlund, 1999). A comparison between measured and simulated energy balance for a dark (box 1) and a light (box 2) awning is shown in Fig. 1. This figure shows that the computer models are accurate since the error with respect to the incident solar radiation is less than 3%. The light awning model slightly underestimates the cooling demand, especially with high solar radiation intensity. Wallénten & Wall (1999) suggest that this is due to the fact that the shading model assumes all transmitted radiation to be purely diffuse.

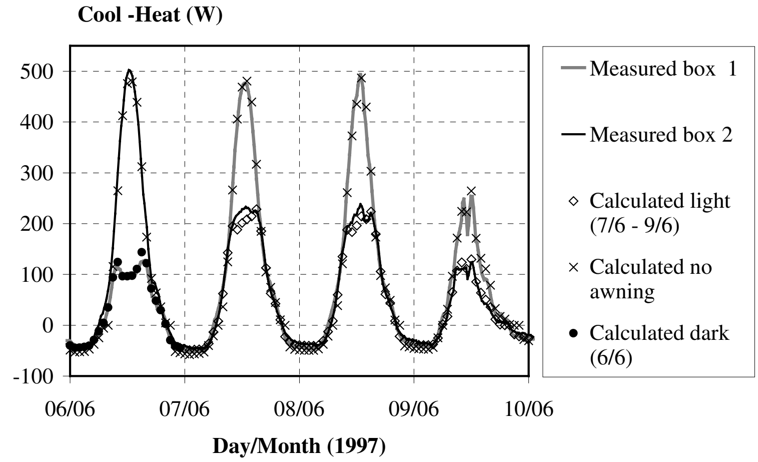


Figure 1 Comparison between the measured and calculated energy balance for the test boxes. The shadings tested were a dark awning on box 1 (drawn down on 97-06-06 and up on 97-06-07) and a light awning on box 2 (up on 97-06-06 and down on 97-06-07).

Similar measurements and tests were performed for external venetian blinds, Italian awnings, fixed overhangs and screens. A comparison between measurements and simulations for blinds and Italian awnings showed that the computer model yields accurate results (Källblad & Wallentén in Wall & Fredlund, 1999).

2.3 Parasol-LTH

Since professionals in the building sector have a variable technical background, it was judged necessary to provide them with a user-friendly tool for shading calculations. An interface to *Derob-LTH* called *Parasol-LTH* has thus been written with architects and building consultants as intended user group. *Parasol-LTH*, which is a Windows 95/98/NT program written in Visual Basic, contains a set of simple dialog boxes (Fig. 2, 3a, 3b) where input information is entered and "sent" to *Derob-LTH*, which performs the calculations. The results of the calculations, which are directly accessible through output boxes in *Parasol-LTH,* are either simple or detailed depending on the input information provided. The current version of the program is in Swedish but future plans include a translation of the interface to English.

2.3.1 Input data. Figure 2 shows the "start" dialog box where the room and window geometry, the climate (location), type of construction, window and shading type as well as level of calculation (simple or detailed) are defined. The dialog box also contains a 3D graphical representation of the room (upper right corner), which is interactively modified as the room geometry and shading device are defined.

The input box defining the room geometry is shown in Fig. 3a. Only one geometry consisting of a rectangular room with one wall and one window facing the exterior is allowed in the current version of the program. Future versions will include a set of more complex room geometries.

Figure 3b shows the dialog box where an awning's width, arm length and slope, horizontal and vertical position as well as optical properties (transmittance, absorptance, emittance) are defined. Input boxes for other types of shades like exterior venetian blinds, Italian awnings, overhangs and screens will also be available in the first program version.

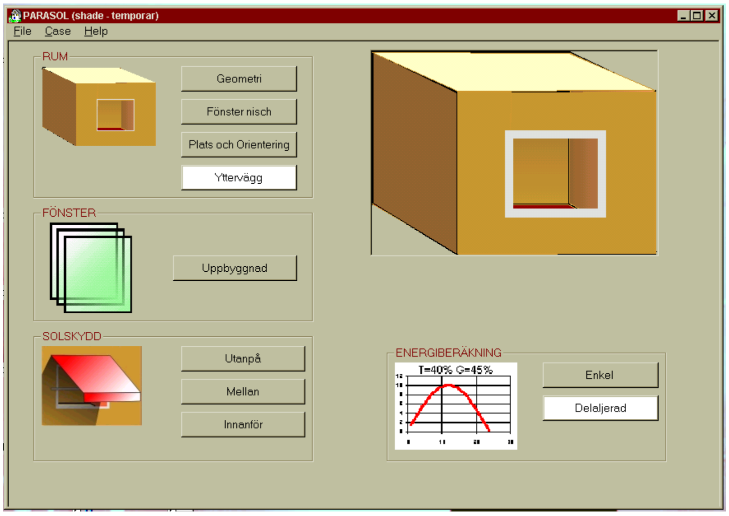
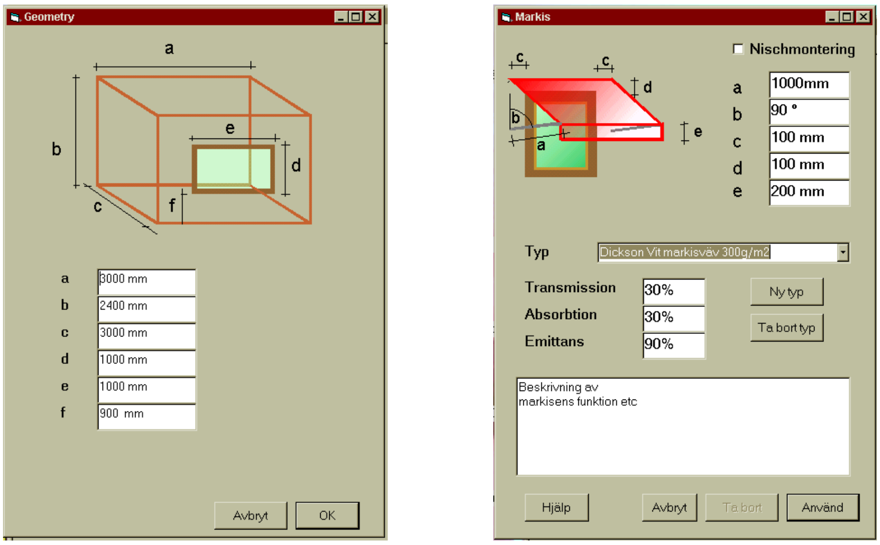


Figure 2 The “start” dialog box.



a 3000 mm
b 2400 mm
c 3000 mm
d 1000 mm
e 1000 mm
f 900 mm

☐ Nischmontering
a 1000mm
b 90 °
c 100 mm
d 100 mm
e 200 mm

Typ Dickson Vit markisväv 300g/m2

Transmission 30%
Absorbtion 30%
Emittans 90%

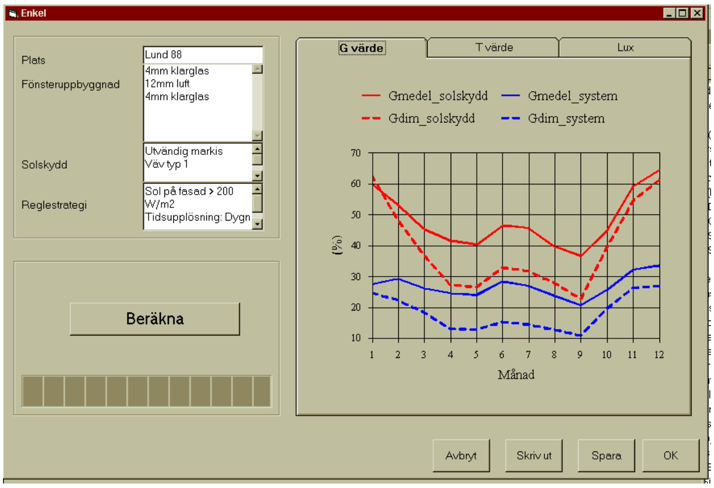
Beskrivning av
markisens funktion etc

a) b)

Figure 3 Dialog boxes to define a) the room geometry and b) the shade type, geometry and properties (transmittance, absorptance and emittance).

Other input information includes descriptions of the window, orientation, climate, walls, etc. For the window, the input box specifies the glazing type and thickness, spacing between panes, gas fills and coatings. The window can either be selected from a predefined library or built up from a choice of glazings, gas fills and coatings. Moreover, the geometry of the window niche can be defined by entering the window offset with respect to the facade and the thickness of the window frame. The walls are defined either as ”light” or ”heavy” construction both for outer and inner walls. For outer walls, the thermal transmission is defined by the U-value (W/m^2°C).

2.3.2 Output data. The output data is either simple or detailed. The simple output data (Fig. 4) consists of either primary (T-value) or total (G-value) transmittance for the shading device or for the shade plus window assembly. In both cases, the transmittance values useful for total energy and peak loads calculations are given in a diagram (right). These calculated values can be saved on a file and exported to another energy simulation program.


Plats: Lund 88

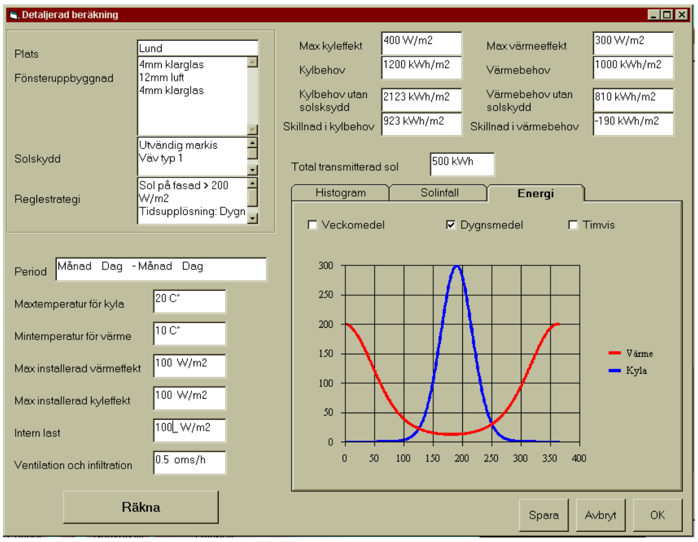
Fönsteruppbyggnad: 4mm klarglas 12mm luft 4mm klarglas

Solskydd: Utvändig markis Väv typ 1

Reglestrategi: Sol på fasad > 200 W/m2 Tidsupplösning: Dygn

Figure 4 Dialog box showing the output data of a simple calculation. The result of the simple calculation (diagram, right) is the primary (T-value) and total (G-value) transmittance of the shade or shade plus window assembly.

The detailed output data (Fig. 5) consists of total and peak cooling and heating loads and indoor temperature fluctuations. The total transmitted solar radiation, the cooling and heating demand for a non-shaded room as well as the difference between a shaded and a non-shaded room are also given (top right). These values can also be saved on a file and exported to another program.



Plats	Lund
Fönsteruppbyggnad	4mm klarglas 12mm luft 4mm klarglas
Solskydd	Utvändig markis Väv typ 1
Reglestrategi	Sol på fasad > 200 W/m2 Tidsupplösning: Dygn
Period	Månad Dag - Månad Dag
Maxtemperatur för kyla	20 C°
Mintemperatur för värme	10 C°
Max installerad värmeffekt	100 W/m2
Max installerad kyleffekt	100 W/m2
Intern last	100 W/m2
Ventilation och infiltration	0.5 oms/h

Max kyleffekt	400 W/m2	Max värmeeffekt	300 W/m2
Kylbehov	1200 kWh/m2	Värmebehov	1000 kWh/m2
Kylbehov utan solsksydd	2123 kWh/m2	Värmebehov utan solskydd	810 kWh/m2
Skillnad i kylbehov	923 kWh/m2	Skillnad i värmebehov	-190 kWh/m2

Total transmitterad sol 500 kWh

☐ Veckomedel ☑ Dygnsmedel ☐ Timvis

Figure 5 Dialog box showing the output data of a detailed calculation. The detailed output data consists of a diagram (right) of monthly, daily or time related energy consumption and peak and total cooling and heating loads (top right).

3. APPLICATION

Parasol-LTH was used to study the geometry and properties (transmittance, reflectance) of a seasonal awning installed in front of an office room under the cooling season (May-Sept.). The room was a 2.9-m wide, 4.2-m deep and 2.7-m high (interior dimensions), south-orientated rectangular space (Fig. 6a) located in Stockholm. The room's triple-pane, clear glass window measured 1.8 m (width) by 1.3 m (height), had a U-value of 1.88 W/m^2°C and a shading coefficient of 0.76. The exterior wall was a standard construction with respect to Swedish norms with a U-value of 0.18 W/ m^2°C. The room had constant infiltration (0.1 ach) and ventilation (10 L/s) rates, internal heat gains from one occupant (90 W), a computer and monitor (120 W) and energy-efficient lighting (10 W/m^2) (assumed under normal work hours). The temperature set points were 20°C (heating) or 24°C (cooling) during work hours (8-17) and 18°C (heating) or 28°C (cooling) the rest of the time.

Fig. 6b presents the incremental annual heating and cooling loads and peak cooling demand as a function of the awning's length. The figure shows that increasing the awning's length significantly reduced the annual cooling demand. However, over a certain length (1.0 m), little additional cooling savings were obtained. The length also had a large impact on peak cooling loads and a moderate impact on the annual heating demand.

Other parameters such as the awning's width, slope, transmittance, reflectance (colour) and seasonal management strategy were also varied in this study. It was found that using a seasonal awning could reduce the annual cooling demand by up to 80% while a fixed awning (in place year-round) increased the annual heating loads by 31%. Both the seasonal management strategy and the length were the factors affecting energy use most significantly while the awning's width, slope, reflectance and transmittance only had a small impact on annual energy use.

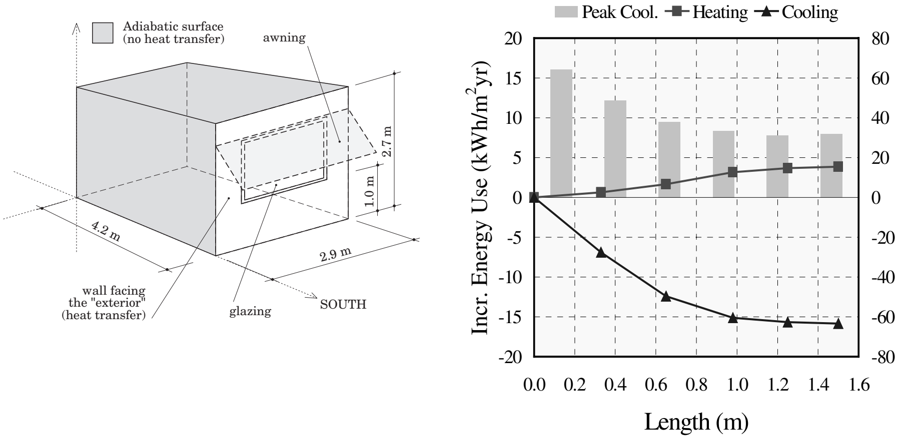


Figure 6 a) Office room and b) incremental annual heating and cooling loads (kWh/m^{2}yr) and annual peak cooling load (W/m^2) as a function of the awning's length.

4. CONCLUSIONS AND FUTURE WORK

A user-friendly computer tool called *Parasol-LTH* has been developed at Lund University's Department of Building Science. The model has been validated experimentally and it has been found that it predicts heating and cooling loads very accurately for exterior shades like conventional and Italian awnings, venetian blinds, screens and overhangs. The model has also been used to study the impact of the design and seasonal management of an awning on energy use in an office room and yielded a set of practical results and recommendations.

The first version of the program is planned to be released in March 2000 and will allow the modeling of exterior shading devices of arbitrary shape and optical properties. The second version will allow the modeling of shading devices between panes, and the third version will handle interior shading devices. Future plans also include translating the interface to English as well as developing control algorithms for shading systems.

5. ACKNOWLEDGEMENT

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