Solar Shading and Building Energy Use

A Literature Review
Part 1

by
Marie-Claude Dubois

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Solar Shading and Building Energy Use, A Literature Review, Part 1.
Lund University, Lund Institute of Technology, Department of Building Science

Lund Institute of Technology
Department of Building Science
P.O. Box 118
SE-221 00 LUND
Sweden

Telephone: int + 46 46 222 73 45
Telefax: int + 46 46 222 47 19
e-mail: bkl@bkl.lth.se
Homepage: http://www.bkl.lth.se

Abstract

Literature in connection with solar shading of buildings and energy use has been reviewed and classified in three main domains: 1) physical properties of shading devices, 2) effect of solar shading on energy use and daylighting and 3) calculation methods to assess the energy performance of buildings equipped with shading devices.

The review showed that the thermal resistance of shading devices has been studied extensively although work on the thermal resistance of devices attached to double and triple pane windows remains to be done. Average and normal incidence optical properties have been determined for most shading devices but solar angle dependent values still need to be measured. No standard measurement procedures have been reported.

Studies of the impact of shading on annual energy use have demonstrated that shading devices reduce the cooling demand in buildings while increasing the heating loads due to loss of beneficial solar gains. Optimal shading strategies are thus climate dependent: in heating-dominated countries, fixed devices with medium to high solar transmittance and high thermal resistance or systems that can be removed in the winter are more energy efficient. Shading strategies for daylit buildings where artificial lighting is replaced by natural light through installation of dimming systems need to be investigated further.

Finally, it was demonstrated that calculation methods associated with energy transfer through shading systems have been developed for awnings, venetian blinds and interior roller shades. Work on model validation as well as development of improved mathematical models for diffuse and ground-reflected radiation flows through different types of shading devices remains.

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Marie-Claude Dubois

1 Introduction

Solar shading affects energy use in a building by reducing solar gains and by modifying thermal losses through windows. Shading devices also influence daylighting levels in a room and the view to the exterior. Shading is thus closely connected with energy use in buildings for heating, cooling and lighting and with the occupants' visual and thermal comfort. Both energy use and comfort are crucial issues. Energy use is related to important economic and environmental factors while comfort affects the well being and productivity of occupants in a building.

Shading of buildings with respect to both energy use and comfort is a complicated task. Fortunately, a large number of studies have addressed this issue and knowledge on this subject is abundant. The main purpose of the present review is to describe and discuss critically a large part of this knowledge related to solar shading and building energy use in order to understand the organisation and extent of knowledge in this field and to identify areas of work which have been neglected or need further investigation. Through critical discussions of the literature, this review also permits the identification of weaknesses in existing research methods and general concepts and makes it possible to define future research purposes and objectives as well as methods which need to be developed to study this subject.

Although comfort is an important factor to consider, the focus of this review is on energy use. Moreover, although this report intends to review most of the important works on solar shading of buildings, some more studies, mentioned at the end of the report, are to be reviewed later. Work connected with daylighting calculation programs, windows and energy use or daylighting and energy use are also discussed here as they relate indirectly to the problem. Studies of solar protective glazing are also included since solar protective glass is the most common alternative to shading and affects energy use and comfort in buildings in ways similar to shading devices.

This review shows that knowledge related to solar shading and energy use in buildings is organised under three essential topics:

1) the physical properties (thermal and optical) of solar protective glazing and shading devices
2) the effect of solar shading on energy use and daylighting in buildings
3) the calculation methods to assess the performance of buildings equipped with shading devices and solar protective glazing

Knowledge of the thermal resistance of shading devices is wide and detailed as this topic has been studied extensively. However, the review shows that work on the thermal resistance of devices attached to double and triple pane windows remains to be done. Concerning optical properties of shading, average and normal incidence values have been determined for most shading devices but solar angle dependent values still need to be measured. No standard measurement procedures are reported in this review.

The review also shows that studies of the impact of shading on annual energy use have demonstrated that shading devices reduce the cooling demand in buildings while increasing the heating loads due to loss of beneficial solar gains. Optimal shading strategies are thus climate dependent: in heating-dominated countries, fixed devices with medium to high solar transmittance and high thermal resistance or systems that can be removed in the winter are more energy efficient. The review also emphasises that shading strategies for daylit buildings where artificial lighting is replaced by natural light through installation of dimming systems need to be investigated further.

Finally, this review demonstrates that calculation methods associated with energy flows through shading systems have been developed for awnings, venetian blinds and interior roller shades. Work on model validation as well as development of improved mathematical models for diffuse and ground reflected radiation transfer through different types of shading devices remains.

Overall, this literature review indicates that knowledge related to solar shading in buildings is abundant but that work on the determination of physical properties of shading devices and on the development of computer programs to assess energy use and comfort in buildings equipped with shading devices still needs to be carried out. As a conclusion, the review suggests that these future advances will allow climate specific shading strategies to be defined for different types of buildings.

2 Properties of solar shading devices

2.1 Thermal transmittance

2.1.1 Review by Grasso, Hunn and Briones (1990)

Since the 60's, many researchers have attempted to determine the influence of shading devices on thermal transmittance of windows. Grasso, Hunn & Briones (1990) reviewed the work of Osizik & Schutrum (1959), Pennington & McDuffie (1970), Dix & Lavan (1974), Grasso & Buchanan (1979), Cukierski & Buchanan (1979), Feather (1980), Tomany (1981), Horridge et al. (1983), Epps et al. (1984, 1987), Lunde & Lindley (1988) on this subject. According to Grasso, Hunn & Briones (1990), the main findings of these researchers can be summarised as follows:

1) The insulation effectiveness is a function of shade type, configuration and the physical properties of the shade fabric.
2) The closer the shading device is to the window, the better the resulting insulation.
3) Sealing edges of draperies around the window increases the thermal performance.
4) The total surface area of the fabric is an important factor to consider; flat or mini-full draperies, whose edges are sealed to the window, provide better thermal insulation than the draperies with greater fullness (Epps et al., 1984). Horridge et al. (1983) found, however, that shirred curtains with fullness widths greater than pleated curtains provide better insulation.

5) Traditional roller shades provide better insulation than do venetian blinds or draperies.
6) Multiple fabric layers (two or three) provide better insulation than single layers, regardless of whether the shades are mounted conventionally or with side tracks sealing the edges to the window. The amount of heat flow reduction is between 15 and 20%.
7) Small separations between lining and drapery are associated with improved insulation.
8) The stitching pattern is an important factor in the thermal performance of multi-layered quilted shades.
9) Tightly woven fabrics are better insulators. A study by Lunde & Lindley (1988) contradicts this finding but it was performed under extreme winter conditions.
10) Drapery fabric weight and fibre content has little effect on thermal insulation.
11) Fabrics with light-coloured backings provide better insulation.
12) Important roller shade fabric characteristics include thickness, weight, and emissivity. Roller shades laminated with metalized Mylar material show great potential in reducing heat loss through windows.

2.1.2 Review by the author

Work by Grasso, Hunn and Briones (1990):

Window type(s):	Single pane, clear glass
Window area(s):	0.85 m² (30% of wall area)
Shading device(s):	Interior draperies
Climate(s):	No solar radiation / temperature difference of 16.7°C (simulated)
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Experimental*
Result(s):	Guidelines: thermal transmittance of draperies (R-values)
Other:	*Using a guarded hot plate apparatus

Grasso, Hunn & Briones (1990) studied experimentally the influence of thirty different draperies with unsealed edges on the thermal transmittance of a window. The study aimed to identify the drapery configuration and fabric physical properties which influence the thermal transmittance. The physical properties considered were: fibre length (*filament* = long or *staple* = short), fibre content (for example, cotton), yarn count (number of *warp* = vertical and *filling* = horizontal yarns per unit area), yarn size (linear density of a yarn), yarn twist (number of turns), fabric weight (mass per unit area), fabric structure (weaving type), colour and finish. A second objective was to compare the thermal transmittance of fabrics of differing opacities. The experiment was performed using a guarded hot plate apparatus under conditions of no solar radiation with a single pane, clear glass window. Statistical techniques such as analysis of variance, t-tests and regression analysis were used to investigate the influence of textile parameters on the thermal transmittance of any other drapery.

The results of the study indicated that with no edge seals, the flat or draped configuration has little impact on thermal transmission. Fabrics constructed with both filament (long) and staple (short) length fibres provided more insulation than fabrics containing only staple (short) length or only filament (long) length fibres. Fabrics with high warp (vertical) and medium filling (horizontal) yarn counts contributed to better insulation (approximately 40% greater in R-value than the measured R-value for the bare window reference case). High warp (vertical) yarn size and medium filling (horizontal) yarn size contributed to lower U-values (approximately 30% greater in R-value than the measured R-value for the bare window reference case). So higher yarn (vertical) count and yarn (vertical) size in the warp (vertical) direction contributed to better insulation. There were significant differences among the fabric structures and their thermal performance but the results were not conclusive on this particular matter. Opaque fabrics (draperies) provided better insulation (by 5%) than transparent or translucent fabrics.

This study showed that the influence of shading devices on heat losses through a single pane, clear glass window can be important, depending on the type, configuration and physical properties of the shade used. The potential improvement in the window U-value should not be underestimated especially if the device is a drapery or a roller shade. However, tests were made with a single pane, clear glass window. If a double pane window with clear glass had been used instead, the best insulating device tested in the experiment would have increased the thermal resistance of the window by 23%. For a triple pane clear glass window, the maximal improvement would be around

15%. For windows with lower U-values than triple pane clear glass windows, the maximal improvement in resistance would be lower than 15%. For shading devices such as horizontal or vertical venetian blinds, the reduction in heat loss can be expected to be lower, especially when the slats are open. Sealed devices would, however, improve the thermal resistance substantially even for double or triple pane windows. Devices such as overhangs or awnings should have negligible impact on thermal transmittance.

Work by Rheault and Bilgen (1989):

Window type(s):	Double pane, clear, heat absorbing and low-e coated glass
Window area(s):	0.141 m² (33% of wall area)
Shading device(s):	Automated venetian blinds between panes
Climate(s):	Canada (Montreal)
Orientation(s):	South
Year/period(s):	14 to 26 April 1987 (validation of program) / October to November 1986 (experiments on thermal resistance)
Energy end-use(s):	Not included
Research method(s):	Experimental* + theoretical**
Result(s):	*Guidelines: thermal resistance of venetian blinds between panes **Validation of a computer program
Other:	*Using a variable temperature calorimeter

Rheault & Bilgen (1989) presented an experimental study on automated venetian blind window systems installed between double pane, clear glass windows. The experimental setting consisted of one full size experiment and one small scale experiment. The experimental results were validated against computer calculations with a theoretical model presented earlier by Rheault & Bilgen (1987a). In the small scale experimental study, various types of interior glass were used (regular, heat absorbing, low emissivity coated) and the thermal characteristic of the whole window unit was assessed.

For the regular and the heat absorbing panes, the thermal resistance did not change with the louvre angle variation. For the window with low emissivity coating on the interior pane, the thermal characteristics were improved by about 58% (for the open louvre position) and by 73% (for the closed louvre position) compared with the regular glass louvred window system. Thus, the authors found that a low emissivity interior pane used together with an automated venetian blind window system would give the best performance during both heating and cooling seasons if the louvre angle is modulated to decrease the shading coefficient (better shade) during the cooling season.

This study contains the same limits as earlier studies by the same authors (Rheault & Bilgen, 1987a, 1987b). Focused on describing the changes in thermal characteristics, it does not provide further indication of the potential energy savings of using such a system. The study is original in that advanced glazing methods are considered in combination with a shading device. However, it would have been interesting if the authors had compared the thermal transmittance of the low emissivity coating window with the automated system with that of the same window without the automated system. This would have made it possible to define how much thermal resistance is due to the shading device.

Work by Lunde and Lindley (1988):

Window type(s):	Double pane, clear glass
Window area(s):	0.85 m² (39% of wall area)
Shading device(s):	Interior: draperies, shades, insulated shutters, polystyrene boards, polyester window insulation board On panes: plastic and acrylic films and various window treatments
Climate(s):	United States (upper Midwest), no solar radiation, no wind flow
Orientation(s):	Any
Year/period(s):	Winter
Energy end-use(s):	Not included
Research method(s):	Experimental
Result(s):	Guidelines: thermal transmittance of various shading devices
Other:	

Lunde & Lindley (1988) studied the effect of 34 different window treatments (draperies, various shades, plastic films, insulated shutters, polystyrene boards, acrylic inside storm windows, polyester window insulation, and several different combinations of window treatments) on a double pane, clear glass window's thermal transmittance through laboratory measurements with conditions of no solar radiation, no wind flow, and sub-zero temperatures.

The study indicated that roller shades (6.3-38.0% reduction), roman shades (17.1-48.0% reduction), films (17.7-23.4% reduction) and other selected treatments significantly reduce heat loss compared with the bare window. Heat loss was reduced by almost 50% when roller shades and roman shades were sealed to the window case.

Roman shades, as a group, appeared to be the most effective heat barriers (17-48% reduction), particularly when sealed to the window frame. As expected, polystyrene boards greatly improved the window resistance to heat loss (37-75% reduction) but the authors mentioned the negative factors associated with it (problems with storage space, handling, aesthetics and poor light transmittance). Draperies tested and the covered cornice did not affect significantly the window heat loss compared with the bare case and combinations of window treatments did not improve the window resistance over single treatments. Overall, the study reasserted that sealing the edges of the window coverings more than doubled the insulation value of the shading devices.

This study generally showed the potential for energy conservation through the use of window coverings as well as the important characteristics associated with shading devices. However, the tests were conducted under artificial conditions (no solar radiation, no wind and constant humidity level).

Work by Horridge, Woodson, Khan and Tock (1983):

Window type(s):	Single pane, clear glass
Window area(s):	Not specified
Shading device(s):	Interior: venetian blinds, translucent rollers, vertical blinds, opaque roller shades, drapery liners
Climate(s):	Cold night time conditions, no wind flow, no solar radiation (simulated)
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Experimental
Result(s):	Guildelines: thermal* and visual** transmittance of shading devices
Other:	*Using a cold box with painted black interior connected to a refrigeration unit **Using slide projector and photometer

Horridge, Woodson, Khan & Tock (1983) investigated the heat flow and the visible transmittance through selected categories of single and multi layered window treatments (venetian blinds, translucent rollers, vertical blinds, opaque roller shades, drapery liners, etc.). The heat losses were measured using a cold box with painted black interior connected to a refrigeration unit used to simulate cold, night time conditions. Wind effects were not simulated. The visible light transmittance was measured using a slide projector and a photometer. The authors studied the influence of the shading device's design and installation procedure, of using multiple layers, of varying the distance to the glass and of using various floor to ceiling installations.

The study showed that, out of 34 cases, 20 individual treatments improved the thermal resistance of the window by 70%. The highest R-value was obtained with an aluminium slats venetian blind. Multiple layers did not improve the window thermal resistance except when the distance between the layers was reduced to 2.54 cm. The installation procedure did not significantly influence the R-values. Also, it was shown that 2/3 of the window treatments tested reduced the visible light by 60-100% and that the window treatments could also significantly increase the thermal resistance of the window. In general there was a reverse relationship between visible light transmittance and thermal resistance.

The study is interesting because it provides R-values for different window coverings. However, some results contradict research results found by other researchers. They should be examined with caution. Note also that the light transmittance was measured using a projector and that the experimental conditions were relatively far from a real sky situation.

Work by Grasso and Buchanan (1979):

Window type(s):	Single pane, clear glass
Window area(s):	0.56 m² (9% of wall area)
Shading device(s):	Interior roller shades
Climate(s):	No solar radiation, Temperature difference of 30°F (1,1°C) and 50°F (10,0°C)
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Experimental*
Result(s):	Guidelines: thermal transmittance of shading devices
Other:	*Using a window thermal transmittance apparatus

Grasso & Buchanan (1979) conducted a study to determine the effectiveness of various roller shade systems to reduce heat losses through windows. The analysis was performed via laboratory measurements using a window thermal transmission apparatus. Radiative, conductive and convective heat transfers were separated on a qualitative basis. The effectiveness of each shade fabric was defined as the percentage reduction of heat loss with the shade in place in the window compared with the heat loss for the bare window (single pane, clear glass).

The study indicated that amongst the conventional systems, 3 shade fabrics resulted in 25-30% reductions in heat loss. The Mylar coated shade—the most effective in reducing heat loss—and the woven wood shade yielded 45% and 34% heat loss reduction respectively. Contrary to results found by Osizik & Schutrum (1959), the authors found that the distance from the shade to the glass was an important parameter with higher reductions of heat loss achieved when the shade was positioned closer to the window. This relationship also appeared when vertical edges were sealed to the side track system. It was also found that multiple layer shades were better insulators, especially if the distance between the different layers was small. The authors also performed an analysis of covariance to determine the most influential characteristics of the shades and found that the following characteristics were important (from most to least important): temperature differential, shade fabric thickness, fabric type, side edge treatment, distance between shade and glass, interaction of fabric type and distance between shade and glass and interaction of the side edge treatment and the distance between shade and glass. In conclusion, the authors established that as thickness of the fabric increased so did the resistance to conduction losses. They also showed that the side edge treatment (sealing) provided a greater reduction of heat loss by reducing the convective heat transfer associated with conventional mounting systems and that side tracks increased the effectiveness of the shade by 10-20% depending on the fabric and the distance between the shade and the glass.

This study identifies some of the important characteristics influencing the insulation value of shades. However, the study is limited to roller shades inside windows and to one temperature difference.

2.2 Solar transmittance

Work by "Architecture et Climat" (1997):

Window type(s):	Any
Window area(s):	Any
Shading device(s):	All
Climate(s):	Belgium
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Not specified (assume from literature review)
Result(s):	Guidelines* in the form of a technical document
Other:	*Also includes topics such as solar factor, visual and thermal transmittance, maintenance, cost, flexibility, durability, visual appearance, natural ventilation, intimacy

A research group in Belgium (Architecture et Climat, 1997) published an interesting technical document aimed at helping consultants and building owners to choose appropriate shading devices. Apart from listing the different shading devices available to the consumer, the authors describe each type of device in terms of solar factor (percentage of energy transmitted through simple or composite glazing) and visual transmittance (percentage of light passing through the glazing). They also discuss aspects such as maintenance, flexibility, cost, visual appearance, durability, natural ventilation, intimacy and thermal insulation provided by the device. They provide examples showing that adding a shading device to an office building can reduce the cooling load by as much as 50%. Tables showing the minimum solar factor of a shading device plus glazing assembly for different building orientations and different types of construction (heavy to light construction) and tables showing the minimal light transmittance according to different orientations and position of the desired lighting level (300 lux) for different periods of the year are also provided.

This document is useful to understand what are the important issues related to shading devices and which physical properties must be taken into account. It also summarises what shading devices are available and what are the problems or advantages related to each. However, this document does not provide clear insights about strategies to adopt in different climatic conditions. It is also unclear how the thermal and optical properties were obtained. No references are mentioned.

Work by Christoffers (1996):

Window type(s):	No window (only prismatic panes)
Window area(s):	Not specified
Shading device(s):	Prismatic panes
Climate(s):	Simulated radiation field for latitude 52°N
Orientation(s):	South
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Experimental
Result(s):	Knowledge: solar transmittance of prismatic panes
Other:	

Christoffers (1996) presents prismatic panes as potential energy savers similar to shading devices. The prismatic panes are designed so that sunlight rays are reflected only under certain angles of incidence such as experienced in the summer. These panes allow heating energy savings in the winter, according to the author, because the use of beneficial solar gains is possible. They also avoid overheating in the summer and, hence, high cooling loads since direct radiation is specifically reflected out of the window. The author presents a study describing the transmission property of such panes based on laboratory measurements with simulated radiation fields for different sun altitudes and azimuths.

The study permitted to exhibit the good switching capacity of the panes. The daily sum of direct radiation on a clear day was reduced by 10% in January and by 90% on a clear day in July. The diffuse radiation was, however, transmitted to 70% (30% reduction).

Although the ability of the prismatic panes to block direct rays in summer was demonstrated, this study does not allow conclusions to be drawn regarding the potential energy savings achievable with these devices under a specific climate. No global energy simulations were performed to verify, for example, the effect of these panes during cloudy days in January. The effect of the prismatic panes during the spring and the autumn should also be verified. It may be found, for example, that beneficial direct radiation is lost in the transition seasons. Also, as pointed out by the author himself, the prisms have the great disadvantage to block all view to the outside. Thus the application would be unacceptable in offices or residential buildings, unless the panels are applied to upper window parts, for example. Note that an exterior manageable venetian blind would provide the same benefits as the prismatic panes (block direct radiation and admit diffuse radiation) without the inconvenience of blocking the view at all times. Finally, it should be noted that the prismatic panes can only be used on the south facade. This limits even more the application of this type of device unless west and east facing devices are developed.

Work by the Department of Energy, Energy Technology Support Unit (ETSU) (1990):

Window type(s):	Single pane, clear glass
Window area(s):	1.5 m² (40% of floor area)
Shading device(s):	Interior: venetian blinds, net and light curtains
Climate(s):	Not specified (but can assume Newport, UK)
Orientation(s):	South
Year/period(s):	April to August
Energy end-use(s):	Not included
Research method(s):	Experimental*
Result(s):	Guidelines: solar and thermal transmittance of some shading devices
Other:	*Using buffer temperature, heat flux mat and thermo couple array

Through a series of experiments, a research team (ETSU) at the Department of Energy (1990) determined the properties of some shading devices (venetian blinds, net curtains and light curtains) which are to be used as inputs in the energy simulation computer program *SERI-RES*. Specifically, the authors defined the effect of window coverings on the amount of solar radiation collected by a window (characterised by the shading coefficient) and the heat loss through the window (characterised by the U-value). Three different measurement techniques (buffer temperature, heat flux mat, and thermocouple array) were used to determine the latter. The experiment was carried out during 5 summer months.

Results of the experiments indicated a fairly high shading coefficient (around 0,80) for venetian blinds and net curtains showing that solar gains through closed blinds can be substantial. This was explained by the fact that blinds do not close entirely and that a warm air layer is formed between the blind and the glazing, creating a solar collector effect. The value of the shading coefficient for permanently closed curtains was around 0,50. The authors thus suggested that venetian blinds and all types of curtains tested were poor shades since even the light curtain (which had the best SC) let 50% of the solar radiation enter the room. Results of the measurements on the thermal transmittance of windows when different coverings are applied indicated that thermal effects of net curtains or venetian blinds were not worth their inclusion in a computer calculation model. However, light curtains did have a significant effect on window heat loss with 20% reduction for a lightweight lined curtain and 40% reduction for a heavy curtain with thermal lining (compared to an uncovered window). The authors concluded that heavy curtains can almost halve the heat loss through a single plane, clear glass window with significant effect on the building energy performance.

This study is only interesting because it presents different measurement methods for the determination of shading coefficient and thermal characteristics of some shading devices. Results may be used in computer simulations based on shading coefficient and U-value concepts.

Work by Steemers (1989):

Window type(s):	Not specified
Window area(s):	Any
Shading device(s):	Exterior fixed (overhangs, fins and egg-crate)
Climate(s):	Latitude 52°N
Orientation(s):	North, east, south, west
Year/period(s):	1 typical year
Energy end-use(s):	Not included
Research method(s):	Theoretical*
Result(s):	Guidelines: shading factor of various shading devices
Other:	*Approach based on the shading and daylight coefficient using a computer program calculating the solar radiation falling on windows

In a short article about solar protection, Steemers (1989) argues that the invention of external shading devices in the form of *brise soleil* is an elemental deconstruction of the loadbearing wall—with frame, skin and *brise soleil* as main layers each specialised to fulfil specific functions. According to this author, if shading devices are used mainly to cut down intense solar radiation, it is important to consider other parameters when the optimum device is to be chosen. Steemers suggests to look also at the quality and the amount of daylighting, the view and the visual and thermal comfort when optimal shading devices must be chosen. According to the author, each latitude and orientation requires a specific response to shading. Also, each location requires a specific shading strategy: where urban or natural obstructions are significant, there should be a transformation in shading from the base of the building to the top. To develop such a strategy for latitude 52° N, Steemers used a computer program to analyse various simple generic shading types (overhang, fins and egg-crate shade) and produce initial performance results.

The author explains that in Central Europe, south and west/east facades receive respectively 40 and 22 times the amount of solar radiation entering a glazed opening on the north facade with no external obstruction. Thus, he argues that north facing shading devices are functionally unjustifiable and non cost effective. Moreover, during summer months, west and east facades receive more gains than south facades but the south receives more solar radiation during autumn and spring. Examining solar gains for latitude 52° N, the author observes that a simple overhang is most effective to cut out summer sun on south facade whilst having little effect on winter solar gains and that vertical fins perform least well for southerly orientations. Egg-crate shading is effective but cuts down too much natural light, view and beneficial winter solar gains while requiring great amounts of material. For west and east, overhangs are better but, as orientation becomes more northerly, fins become very effective and overhangs of little use. The author defines a measure for optimum conditions under a shading device as the *yield* of a device i.e. the product of the shading and daylight coefficients. Plotting annual yield curves for daylight effectiveness confirms the first observations made by the author: for southerly orientations, overhangs are most effective to minimise solar gains while they optimise daylighting levels. Egg-crate shades perform only marginally better than fins because of increased obstructions to daylight. For west and east facing windows, overhangs perform better although differences between overhangs, fins and egg-crate shades are small. Fins are marginally better than egg-crate. Fins are the most suitable for the north facade.

Arguments leading the author to conclude that the best shading devices are fixed overhangs outside the building are mainly based on comparisons between relative *yields* of the devices which are based on the shading and daylight coefficients. This does not say anything about real energy use in a building subjected to different shading devices with definite yields. For certain climates, higher shading coefficients may be better in terms of energy savings.

Work by Hoyano (1985):

Window type(s):	Single pane, clear glass
Window area(s):	Not specified
Shading device(s): (vegetal)	Exterior vine sunscreens
Climate(s):	Japan (Tokyo)
Orientation(s):	West
Year/period(s):	2 summer seasons: 1979, 1981
Energy end-use(s):	Not included
Research method(s):	Experimental*
Result(s):	Knowledge: solar transmittance and temperature fluctuations behind vine sunscreens
Other:	*On a 2-story detached house: measurement of temperature fluctuations and cross ventilation in the room

Through experimental measurements during 2 summer seasons on a 2-storey detached house, Hoyano (1985) studied the effect of vine sunscreen (ivy) covering a west wall on temperature fluctuations, solar radiation and cross ventilation in a veranda. The author first determined solar transmittance of the vegetal sunscreen through measurements and its equivalent shading coefficient. He also determined convective heat transfer coefficient of the wall covered with the screen.

The study showed that the mean solar transmittance of the vine sunscreen was 2-7% depending on the foliage and that most of the influence of solar radiation on the indoor thermal environment could be eliminated by providing such a sunscreen. It was also shown that a volume of dead air was generated within the ivy sunscreen to have an unfavourable effect on the convective cooling, although the amount was small since the outside surface temperature of the exterior wall with an ivy screen was lower than that without ivy sunscreen at night. It was thus demonstrated that the solar radiation on the window covered with the screen was only 25% of that of the screenless window. The vine sunscreen was especially effective for sun shading when the solar latitude was low. The temperature of the veranda covered with the screen was 2-4°C lower in the daytime than the temperature of the screenless room. This was accomplished in spite of drastic reductions in air velocity when the screen was used. After 1800 hours, the temperature of the room with the screen was higher than for the screenless room. It was also shown that there was no significant difference between the relative humidity of the rooms with and without the screen. The cross ventilation ratio without the screen was 46% while the value with the screen was reduced significantly to 17% .

The study is interesting because it shows the potential use of vegetation as shading devices. However, it is not shown by how much the shading device can reduce the energy use. The study is limited to one climate, one orientation and one type of shading device, one window size and one building. Comparison with the bare case only does not allow the development or selection of appropriate shading strategy. The application of vine sunscreens is doubtful for building applications in cold climates where some shading might be necessary in intermediate seasons and foliage may not be available.

Work published in the Architect's Journal (1976):

Window type(s):	Clear and heat absorbing glass
Window area(s):	Any
Shading device(s):	Exterior fixed shading devices Interior: venetian blinds, curtains Shades between panes
Climate(s):	Any
Orientation(s):	Any
Year/period(s):	Not specified
Energy end-use(s):	Not included
Research method(s):	Not specified (assume from literature review)
Result(s):	Guidelines: solar shading of buildings
Other:	

A review of different shading devices and of the advantages and problems associated with them is presented in an issue of the Architect's Journal (1976). In this review, the author compares the savings that can be achieved with different "cooling" methods such as increasing ventilation rates, changing window area, or using heat absorbing glass for both high and low thermal capacity buildings. The author shows that very large ventilation rates must be set to match reductions in temperature offered by the use of shading devices. Increasing ventilation rates would increase energy use and bring some comfort problems due to high air movements. Reducing window area, on the other hand, has the great disadvantage of reducing some beneficial solar gains in the cold season, reducing the view to the outside and the admission of daylight. The author comments that using shading devices is the best way to improve comfort and lower energy use in buildings.

According to the author, external shading devices provide the most effective form of solar control and are generally about 30% more effective than internal blinds, which can only reflect a small part of solar radiation and release some of the heat they absorb back into the building. Heat absorbing glass and devices set between double panes are approximately 15% more effective than internal blinds. Also, the effectiveness of curtaining for insulation purposes is largely a product of the layer of still air trapped between curtain and glass. Curtain weight is not important as long as the curtain is relatively impermeable to air. Blinds should not overlap radiators so that direct heat would be lost to the window glass. Light colours for internal blinds are 20-30% more effective than dark ones. For external devices, however, dark colours absorb more heat and dissipate it outside the building. When the external blinds are not directly next to the glass, less incident radiation is reflected through the glass if dark coloured devices are used than would be the case if light coloured devices were used instead.

This article is too general and does not give specific recommendations on strategies to adopt for one specific climate. Information about the important characteristics of shading devices and a listing of the different kinds of devices available on the market is, however, useful but the article is too old to represent the shading devices used in practice today.

Work by Olgyay (1963):

Window type(s):	Clear, reflective and heat absorbing glass
Window area(s):	Any
Shading device(s):	Interior: venetian blinds, roller shades, insulating curtains Exterior: shade-screens, metal blinds, trees, awnings, various fixed devices, various movable devices
Climate(s):	Not specified
Orientation(s):	Any
Year/period(s):	Not specified
Energy end-use(s):	Not included
Research method(s):	Not specified (assume from literature review)
Result(s):	Guidelines*
Other:	*Also includes a method to determine minimal shading required based on the comfort zone, shading mask and sun path diagrams

The chapter on solar protection by Olgyay (1963) is amongst the early writings on shading. In this chapter, the author compares heat flow through opaque wall and clear pane windows and on differently orientated surfaces to show the importance and potential of shading, especially for west, east and south facades. He then compares the effectiveness of different shading devices according to their characteristics (the method employed, their colour and position) based on the calculation of their respective shading coefficient. He finally presents a method to determine shading needs based on comfort zone, sun path diagrams and the shading mask method.

The author showed that the use of off-white colours for venetian blinds leads to 20% more shade protection than dark colours, and that the figure was higher (40%) for roller shades and lower (18%) for inside curtains. He also asserted that protection was more effective (by about 35%) if the device was positioned outside the building than inside since exterior shading devices dissipate the absorbed solar energy to the outside air. Finally he classified the shading methods from worst to best according to their shading coefficient as follows: venetian blinds, roller shades, tinted glass, insulating curtains, outside shade screen, outside metal blind, coating on glass surface, trees, outside awning, outside fixed shading device, outside moveable shading device.

Although Olgyay identified some of the important characteristics of shading devices and factors that affect solar protection, his work mainly focused on the shading effect itself and not on energy use, daylighting or comfort. The comparison is entirely drawn from the shading coefficient value. The shading coefficient is an average value which does not represent conditions at different solar angles and does not give indications about energy use. It is only a mean number which allows a comparison of the shading provided by different shading devices. The exterior fixed shading devices are placed amongst the best shading methods while it was subsequently demonstrated, by a number of authors (see, for example, Hunn et al., 1990, 1993), that these devices are poor performers in terms of energy use on an annual basis in heating-dominated climates. Fixed exterior devices provide better shading during the cooling season but they are responsible for large losses of beneficial solar gains during other seasons and provide no improvement in the window U-value.

3 Effect of shading devices on energy use and daylighting

3.1 Consideration of heating and cooling loads

3.1.1 Review by Dix and Lavan (1974):

Dix & Lavan (1974) report that work on shading devices dates back to 1940 when Peebles (1940) studied, in a small test house, the reduction in heat intakes, especially solar heat, provided by window shades. Peebles found that light coloured shades reduced heat gain by as much as 55% in the summer and heat loss by 40% in the winter. Later, Lund (1957) examined the ability of reflective window shades to reduce convective (non-solar) cooling and heating loads. Lund found that aluminium foil shades laminated to cloth reduced heat losses by 53% (unsealed) and 58% (sealed). Light-coloured cloth or paper shades provided heat loss reduction of 40%. Jordan & Threlkeld (1959) studied the effect of roller shades sealed to the window on the heating and cooling loads including solar radiation effects. The same year, Ozisik & Schutrum (1959) tested the effect of unsealed roller shades on energy transfers through windows. They showed that a reduction of heat gain of the order of 75% (thus reducing cooling loads by 75%) was achievable with white, opaque window shades.

3.1.2 Review by the author

Work by Cho, Shin and Zaheer-Uddin (1995):

Window type(s):	Double pane, clear glass
Window area(s):	Not specified
Shading device(s):	Interior venetian blinds
Climate(s):	South Korea (Seoul)
Orientation(s):	Not specified
Year/period(s):	1 typical year
Energy end-use(s):	Heating and cooling
Research method(s):	Theoretical*
Result(s):	Guidelines: management of venetian blinds with respect to energy use Computer module** to plug into *TRNSYS*
Other:	*Also includes a validation with experimental data from Hayashi et al. (1989) **Calculates dynamically the angle dependent solar-optical properties of venetian blind and window system

Cho, Shin & Zaheer-Uddin (1995) developed a calculation module to connect with the energy simulation program *TRNSYS* to assess the effect of interior vene-tian blinds installed on the south facade on the energy use of a building. The model was validated against experimental data obtained by Hayashi et al. (1989). Using the blind calculation program, they analysed the effect of slat characteristics such as angle and colour on heating and cooling loads for a building in Korea. The slat angle was varied by 20° intervals; it was not an automatic system. The building studied had double pane, clear glass windows.

Results of the study indicated that the building with venetian blinds required less heating during night time but that this advantage was lost during daytime because of reduced solar heat gains. The blinds reduced cooling loads by 9% at night and by 10-40% during daytime. Overall, the blinds reduced the heating load by 5% and the cooling load by 30%. The slat angle had a significant effect on the cooling loads during daytime and lower slat absorptance (white slats) was desirable to reduce both heating and cooling loads. The optimal slat angle was 20° (view upwards from inside) during the winter and -60° (view downwards from inside) during the summer, with all slat colours.

This study was limited to one building in the climate of Seoul and to the case of double pane, clear glass windows with interior venetian blinds. The blinds were only installed on the south facade of the building. Energy savings could be different if the blinds were installed on the other facades or if the window areas were changed. However, the results were obtained with a program taking into account the sun angle and incorporating hourly transmittance, reflectance and absorptance values into the dynamic energy calculation program. The program was also validated against experimental data and agreement between computer calculations and experimental measurements was demonstrated.

Work by Bilgen (1994):

Window type(s):	Double pane, clear glass
Window area(s):	2.59 m² (72% of wall area)
Shading device(s):	Automated venetian blinds between panes
Climate(s):	Canada (Montreal)
Orientation(s):	One (not specified which one)
Year/period(s):	4 consecutive days in October
Energy end-use(s):	Heating and cooling
Research method(s):	Experimental*
Result(s):	Knowledge: impact of automated venetian blinds between panes on energy use
Other:	*Full size experiments, no internal loads

Through a full-size experiment in 2 experimental cells, Bilgen (1994) studied the thermal performance of automated venetian blind systems installed between double pane, clear glass window units in the climate of Montreal. Measurements were recorded during 4 consecutive days in October.

The results of the experiment indicated that the heating requirements with the automated venetian blind window system were higher by 4-6% due to the loss of beneficial solar gains while the cooling (or ventilation) requirements were lower by 69-89%.

The study only applied to 2 small experimental cells oriented in one direction (not specified in the article) in one climate and during one season. Energy use might differ if the study applied to an entire building with internal loads, in a different climate and season. Blind performance might also differ according to the window orientation, type and size. However, the results obtained in this study appear more realistic than the ones obtained in other works co-authored by Bilgen (Rheault & Bilgen, 1987a, 1987b, 1989) in view of the results obtained by Cho et al. (1995) and Hunn et al. (1990, 1993).

Work by Hunn, Grasso, Jones and Hitzfelder (1990, 1993):

Window type(s):	Double pane, clear, reflective and heat absorbing glass
Window area(s):	31% of wall area (small office) / 46% of wall area (high rise office)
Shading device(s):	Interior: shades, blinds, drapes, curtains, solar screens Exterior: overhangs, awnings, fins
Climate(s):	United States (Minneapolis)
Orientation(s):	North, east, south, west
Year/period(s):	1 typical year
Energy end-use(s):	Heating and cooling
Research method(s):	Theoretical* (parametric study)
Result(s):	Guidelines: strategy for shading buildings in heating dominated climates
Other:	*Using *DOE-2* computer program: solar angle dependent properties of shades were only calculated for exterior fixed devices.

Works by Hunn, Grasso, Jones & Hitzfelder (1990, 1993) are amongst the rare attempts to develop an appropriate shading strategy for buildings located in heating dominated climates. Through a parametric study using the program *DOE-2*, the authors studied the effects of various exterior and interior shading devices on annual energy use, peak electric demand, and energy cost savings in single family houses, a small and a high rise office and a school in Minneapolis. The shading devices tested were either window attached (shades, blinds, drapes/curtains, tinted windows, reflective coatings and solar screens) or exterior fixed devices (overhangs, awnings and side fins). All strategies were compared with double pane clear glass windows except for the high rise office case where double pane tinted glass was used as reference.

The study indicated that while the best performing devices had annual cooling energy savings ranging up to over 30%, the annual energy cost savings were only 4% for residences, 10% for the offices and less than 1% for the school. This was explained by the relative importance of the heating versus the cooling seasons, the inclusion of demand charges in utility rates for commercial buildings, and different occupancy patterns. The study further indicated that while summer peak demand reductions were significant: 20% for houses, 12% for offices and 3% for the school, the potential energy cost savings were highest in offices (7-13%). One of the most important findings was that, as a group, the interior devices (including solar screens) performed better than exterior fixed devices in terms of energy cost saving and peak demand reduction because interior devices shade the entire window while providing additional insulation. Exterior fixed devices were often net energy losers. While insulating properties (U-value) of shading devices had a strong effect on the residential energy cost savings, they had only a moderate effect on the non residential energy cost savings. The U-value had a weak effect on the residential peak demand reduction and virtually no effect on the non residential peak demand reduction. For the offices, the top 3 performing shading devices were: the high performance glazing (low-e + reflective coating), the solar screen (louvred, black, very low SC=0.10; seasonal for the small office and annual for the high-rise) and the reflective glass both in terms of energy cost saving (5-13%) and peak demand reduction (9-16%). In any case, the absorbing glass and the overhang plus fins were almost always poor performers or resulted in net increase in energy use. In fact, reflective glass, tinted (absorbing) glass, annual solar screen and overhang plus fins resulted in increases in annual energy use in the small office. As a general rule, it was found that the shading strategies that decreased radiation yet provided some improvement in U-value during the heating season were the most effective in reducing energy costs.

The main drawback of this study is that no experimental measurements were ever made to confirm the results. Moreover, for the interior, manageable devices, the shading coefficient value was used in the model for any hour of simulation. (This was not the case for exterior devices where the shading coefficient was calculated on an hourly basis). As pointed out by Mc Cluney (1991), the shading coefficient is a single number indicator of normal incidence (or a weighted average over a range of incidence angles) of solar heat gain for the purpose of comparing different fenestration products. For energy analyses including hourly building performance simulation calculations, angle dependent values of the solar heat gain coefficient should be used instead. Apart from this, the study was limited to the climate of Minneapolis and a few fixed exterior devices (only two different overhangs, for example). Fixed exterior devices were never applied to the north facade and manageable devices were always fully opened during the heating season and always fully closed at night, a rare situation for manually managed devices. Furthermore, no complex cases including complex fenestration systems and a shading or multiple shading systems were studied (for example, a high performance glazing system combined with a venetian blind). No devices between panes were analysed and awnings were not considered for offices because they are not typically used in the United States (not necessarily true for other countries). Another drawback is that the study mainly focused on energy cost savings and not energy use reduction. In other countries where energy costs are higher, results might show that shading saves more money (as well as a lot of energy). Finally, the study did not attempt to assess the impact of shading on daylighting, visual and thermal comfort and no account was taken in the computer calculation of the reduction in infiltration rates caused by the addition of shading devices although it was demonstrated that this parameter can be an important source of heat loss (or gain) in windows.

Work by Pletzer, Jones and Hunn (1988):

Window type(s):	Single pane, clear, reflective and heat absorbing glass
Window area(s):	12, 13, 15% of floor area
Shading device(s):	Interior: louvered blinds, draperies, curtains, planar roller shades, shutters Exterior: solar screens, awnings, overhangs, recessed windows, vegetation
Climate(s):	United States (Austin, Texas)
Orientation(s):	North, east, south, west
Year/period(s):	1 typical year
Energy end-use(s):	Heating and cooling
Research method(s):	Theoretical* (parametric study)
Result(s):	Guidelines: strategy for shading houses in cooling dominated climates
Other:	*Using *DOE-2* computer program

Using the dynamic energy calculation program *DOE-2,* Pletzer, Jones & Hunn (1988) studied the effect of shading devices on annual heating, cooling, and total energy use, on summer peak electric demand, and on energy cost savings in single family residences in Austin, Texas. A variety of interior (louvred blinds, draperies and curtains, planar roller or hanging shades and shutters) and exterior (solar screens, awnings, overhangs, recessed windows and vegetation) shading devices as well as reflective and tinted (absorbing) glazing options were compared with single pane, clear glass windows in 3 different (small, medium and large) typical gas heated residences. A linear regression analysis permitted correlation of normalised heating and cooling energy savings as a function of shading performance parameters to predict savings of any shading device applied to any other single family residence.

Most of the results of this study were later confirmed by the work of Hunn et al. (1990, 1993). For example, it was found that, as a group, the interior strategies (including solar screens) performed better than the exterior ones in terms of energy cost savings. Interior devices combine good shading with improvement in U-value. It is worth noting, however, that all but two interior strategies required less energy for heating than the base case. Tinted windows were the worst interior strategy with only 1-3% annual energy cost savings. Exterior shading devices were generally modest energy savers but they reduced significantly the summer peak loads (more than 7%). Vegetation generated more energy savings than overhangs but awnings were generally the most effective exterior strategy because the side pieces blocked a greater portion of diffuse radiation. While annual cooling energy savings for the five best shading strategies ranged from 22-32%, annual energy cost savings were, at most, 14%. Summer peak reductions were 4-22%. Amongst the original findings of this study was that the elimination of solar gains (SC=0) resulted in annual energy cost savings of 7-9% and peak load reduction of 29%. The elimination of all windows yielded energy cost reduction of 12-19% and peak load reduction of 29% (energy use was reduced by 7-13%). Apart from setting the optimal limits for potential energy cost savings from shading (7-9%), this outlined the fact that, even in a cooling dominated climate like that of Austin, heating loads do contribute significantly to annual energy use and cost, and therefore, the insulation value of shading devices or windows is an important parameter to consider. The study also indicated that the use of clear storm windows (double pane) and a 30% reduction in infiltration were only half as effective in reducing annual energy cost as the best shading strategy (the best solar screen). Finally, it must be mentioned that, according to the authors, the building orientation, distribution of shading and building size and integrity had a negligible effect on the annual energy use, cost and summer peak demand.

Like the more recent work of Hunn et al. (1990, 1993), this study contains limits regarding the method (no experimental measurement, shading coefficient concept approach in the method, infiltration not taken into account) and the focus (on energy cost rather than energy use). Also, it should be mentioned that no low-e coating glazing was tested despite the fact that the authors demonstrated the importance of the U-value parameter with respect to annual energy use.

No multiple strategies with complex fenestration systems and multiple shading devices were studied. Daylighting and comfort were not taken into account.

Work by Harkness (1988):

Window type(s):	Single pane, clear glass
Window area(s):	Any
Shading device(s):	Exterior fixed overhangs
Climate(s):	Australia (Brisbane)
Orientation(s):	Any
Year/period(s):	4 summer months
Energy end-use(s):	Cooling
Research method(s):	Theoretical* (parametric study)
Result(s):	Guidelines (in the form of nomograms): exterior shading devices and cooling energy use
Other:	*Using the computer program *TEMPAL* (Univ. of Melbourne)

After explaining that 200 buildings in Singapore retrofitted with either reflective or heat absorbing glass experienced no energy savings (due, in most cases, to a necessity to increase lighting), Harkness (1988) presents the results of a small investigation where the effect of exterior precast concrete panels acting as shading devices on the energy use of an office building in Brisbane, Australia, is examined. The conclusions are drawn from computer simulations with the program *TEMPAL* (University of Melbourne). The author also presents nomograms which may be used by building designers to estimate the reduction in solar loads by changing various combinations of window areas and sunscreen projections.

Results of the simulation indicated that the double pane, green, heat absorbing glass windows in a flush facade resulted in reduction of energy totals for cooling for the four summer months studied compared with using single pane clear glass. However, the use of single pane clear glass with precast exterior panels acting as shading devices yielded superior reductions in cooling energy loads (50%) for the four summer months studied. The author concluded that exterior fixed shading devices associated with clear glazing should be used instead of special glazing windows.

Conclusions of the study are drawn without looking at the loss of beneficial solar gains in the winter and the reduction in lighting levels. It would be necessary to run simulations over a whole year and assess the overall energy use including the lighting parameter. Results of the study are, moreover, only applicable to the climate of

Australia and to one building type with high internal loads. Finally, no experimental measurements were made to validate the computer simulations.

Work by Rheault and Bilgen (1987a, 1987b):

Window type(s):	Double pane, clear glass
Window area(s):	Not specified
Shading device(s):	Automated venetian blinds between panes
Climate(s):	Canada (London, Ontario)
Orientation(s):	Not specified
Year/period(s):	February
Energy end-use(s):	Heating
Research method(s):	Theoretical*
Result(s):	Computer program + knowledge: heating energy use and automated venetian blinds
Other:	*Using computer model developed; this model was not validated

Rheault & Bilgen (1987a) developed a theoretical model for the dynamic calculation of heat transfers through double pane windows with an automated venetian blind system between the panes. They used this computer model to calculate and compare the energy use of a south oriented room in London (Ontario) with and without the automatic louvre system.

The study indicated that the window with the automatic louvre system reduced heating energy by 30% compared with a window with absolutely no shading device.

The study was limited to a small room (10 m^3), oriented in one direction (south), in one climate only (London) during one single period in the winter (February). The scope of the study was thus narrow and did not permit wide generalisation about appropriate shading strategies to be used in cold climates. More crucially, the theoretical model was not verified experimentally. This might explain the results obtained. As found subsequently by other researchers (Bilgen, 1994; Cho et al., 1995; Hunn et al., 1990, 1993), shading devices tend to reduce useful solar gains in winter and increase the heating load during daytime. In theory, this loss should offset the improvement in U-value obtained due to the presence of the louvre system. It is surprising to find that lowered solar gains result in heating load reduction.

Window type(s):	Double pane, clear glass
Window area(s):	*2.58 m² (72% of wall area) / **Not specified
Shading device(s):	Automated venetian blinds between panes
Climate(s):	Canada (London, Ontario)
Orientation(s):	One (not specified which one)
Year/period(s):	1 single typical summer (July) and winter (February) day
Energy end-use(s):	Heating and cooling
Research method(s):	Experimental* + theoretical**
Result(s):	Guidelines: automated venetian blind systems and energy use
Other:	*Validation of computer program **Calculation of energy use with the computer program developed

In a second study, Rheault & Bilgen (1987b) validated experimentally the previously developed theoretical model (Rheault & Bilgen, 1987a). On average, experiment and model agreed with 7% (max. 18%) difference for surface temperatures, and 6% (max. 8%) difference for radiation. Using this computer model, they studied the effect of the automated blind system on a building energy use located in London (Ontario) for typical summer and winter days. The building had double pane, clear glass windows.

The study indicated that the thermal resistance of the system with louvres was 13% higher than the one without louvres. It also showed that it was possible to achieve average daily energy savings of 91% in the summer and 70% in the winter.

The authors only considered one single day in winter and summer; the study did not assess average energy economies over longer periods. The study was also limited to one orientation (not specified in the article which one), one climate, one window size and one type of shading device. As pointed out earlier, the results obtained are somewhat surprising. As other studies showed some years later (Bilgen, 1994; Cho et al., 1995; Hunn et al.,1990, 1993), the louvre system would be expected to yield additional energy use in the winter due to lowered solar gains during the day. At night, it is possible that the louvred system is responsible for a lower U-value, but reductions in heating energy of the order of 70% appear high.

Work by McCluney and Chandra reported by Germer (1984):

Window type(s):	Single pane, clear and heat absorbing glass
Window area(s):	1.49 m² (% of wall area not specified)
Shading device(s):	Exterior: "Bahama" shutters, awnings, overhangs Films and screens on panes
Climate(s):	United States (Florida)
Orientation(s):	North, east, south, west
Year/period(s):	1 typical year
Energy end-use(s):	Heating and cooling
Research method(s):	Not specified (suppose theoretical)
Result(s):	Guidelines: shading devices versus energy use
Other:	

In a brief article, Germer (1984) reports the work of McCluney & Chandra from the *Florida Solar Energy Centre* on shading devices and energy use in the climate of Florida. Mc Cluney & Chandra assessed the effectiveness of different shading devices in reducing solar heat gain. They presented the solar radiant heat gains of 7 different window shading systems (tinted glass, Bahamas shutter, films, screens, translucent and opaque awnings and overhangs) and compared it with the solar heat gain of one reference single pane, clear glass window. The annual average solar heat gains are presented for four orientations.

The study showed that the heating season penalty due to shading devices was smaller than the cooling season benefits with a net annual energy saving. The study also indicated that all orientations yielded considerable heat gains—even the North facade on a clear day—because of the ever-present diffuse radiation component due to high humidity and cirrus clouds. All shading options thus yielded savings for all orientations. Exterior devices such as overhangs, awnings and window screens produced the best annual cooling savings with the smallest heating season penalty. Window films were the next best performers and tinted glass the worst performer in terms of annual energy use. However, it should be mentioned that there was a small difference between the Bahamas shutters, the films, the window screens and the translucent awnings.

The methodology used in this study is not clearly explained. Also, results of this study should be verified with an appropriate building energy performance simulation program. Results seem to be obtained through simple, steady-state hand calculations.

Work by Treado, Barnett and Remmert (1984):

Window type(s):	Single pane, clear glass
Window area(s):	*55% of wall area / **40% of wall area
Shading device(s):	On pane: solar screens, films and shades
Climate(s):	United States (Washington DC, Chicago, San Jose, Phoenix, Atlanta, Boston, Houston)
Orientation(s):	*North, east, south, west / **South
Year/period(s):	1 typical year
Energy end-use(s):	Heating and cooling
Research method(s):	Theoretical* (parametric study) + experimental**
Result(s):	Guidelines: energy use and shading devices
Other:	*Using computer program *DOE-2* **Measurement of the solar and thermal transmittance of 3 solar screens

Using the program *DOE-2*, Treado, Barnett & Remmert (1984) performed annual energy simulations of a typical office building in 7 different climatic locations in the United States (Washington DC, Chicago, San Jose, Houston, Phoenix, Atlanta, Boston) in order to evaluate the effect of solar shading on cooling/heating and annual energy use as well as comfort in office buildings. They also determined the cost effectiveness of solar shading through life-cycle cost analysis. Moreover, before simulation, the authors performed measurements of solar and thermal performance characteristics of three solar screens. Thereafter, they input the results of the measurements in the computer model, along with other values of thermal transmittance and shading coefficient of a total of 13 different shading systems.

The study showed that solar screens can reduce annual energy use and improve comfort significantly. The economic analysis also indicated that while solar shading can be cost effective, the cost effectiveness varies as a function of climate, energy performance, first cost and expected life of the shading device. Most importantly, results of the simulations showed that, in all cases, solar shading resulted in increased heating energy use and decreased cooling energy use. The net energy savings occurred only if the reduction in cooling energy use exceeded the increase in heating energy use. Sometimes, money savings occurred if the cost of cooling decreased more than the increase in the cost of heating. Solar shading proved to be more beneficial to buildings cooled all year but shading lowered overheating in perimeter offices significantly in summer-cooled buildings in all types of climates. In general, it was found that electricity use (not heating energy) decreased with decreasing shading coefficient (better shade). On the other hand, heating energy use increased with decreasing shading coefficient. Lower U-values resulted in slightly smaller electricity use and significantly smaller heating energy use. Total energy use was, thus, climate dependent: cooling dominated cities had a lower energy use with a lower shading coefficient while heating dominated cities exhibited just the opposite trend. In cooling dominated climates, energy, economic and comfort considerations all favoured a low shading coefficient while in heating dominated climates improved comfort conditions required a lower shading coefficient than the most cost effective device which, in turn, required a lower shading coefficient than the most energy effective device.

Because it makes it possible to compare the results between different climates, this study is an important contribution to the knowledge of solar shading devices. However, it is limited to one specific building with one specific window-to-wall ratio. Solutions are also only compared with one specific type of glazing (single pane, clear glass). Regarding the method, it is interesting that measurements were performed to determine the optical and thermal properties of the solar screens. However, it appears that only the normal values (and not the solar angle dependent values) were input in the computer calculation. Results of the simulations were compared with measurements of energy requirements of the real building located in Washington to validate the computer simulations. However, the reference climate year used for the simulation was different from the year when the measurements were made. Daylight was not considered and only fixed shading systems were used. Movable devices could have proved to be cost effective and better energy savers in heating dominated climates.

Work by Treado, Barnett and Kusuda (1983):

Window type(s):	Single pane, clear glass
Window area(s):	*55% of wall area / **1.48 m² (52% of wall area)
Shading device(s):	6 different window films on panes
Climate(s):	United States (Washington DC, Chicago, San Jose, Phoenix, Atlanta, Boston, Houston)
Orientation(s):	*North, east, south, west / **Any
Year/period(s):	1 typical year
Energy end-use(s):	Heating and cooling
Research method(s):	Theoretical* + experimental**
Result(s):	Knowledge: energy use and window films
Other:	*Using computer program *DOE-2* **Measurement of thermal-optical properties of the window films

Using the energy simulation program *DOE-2*, Treado, Barnett & Kusuda (1983) studied the impact of 6 different window films added to single pane, clear glass windows on energy use and cost savings of a typical office building located in 7 different cities in the United States (see Treado, Barnett & Remmert, 1984). The thermal and optical properties of the films were measured and input in the computer model. Results of the computer simulations for the Washington case were compared with actual metered energy use to validate the building model and simulation procedure.

The parametric study showed that solar films can be effective in reducing energy requirements and costs in areas with high cooling loads with less savings in areas with smaller cooling loads and no savings at all in regions with important heating loads. The authors thus suggested that solar films should be used only in the southern half of the United States. In all cases, the films contributed to an increase in annual heating energy use due to the reduction of beneficial solar gains and a reduction in cooling energy requirements in almost all the cases. Net reduction in annual building energy requirements occurred only if the reduction in cooling energy exceeded the increase in heating energy use. Thus the magnitude of the energy cost savings also depended on the relative cost of cooling and heating. The authors underlined that none of the solar films tested produced a net annual reduction in energy use for Chicago, Boston and San Jose. Optimum shading coefficient was dependent on the magnitude of cooling energy requirement with lower values of shading coefficient effective in regions with large cooling loads. As a general rule it was found that solar films having both a low U-value (low emittance films) and a low shading coefficient were most effective in reducing overall energy use. The cost effectiveness of the solar films was found to be dependent on glass orientation, initial cost and expected life of the film.

This study contains the same overall qualities and limits as the more recent work of Treado, Barnett & Remmert (1984) regarding the method used (shading coefficient). However, this study does not take into account comfort and daylighting. One positive aspect of the study is that results of the simulation were verified against measured energy use for at least one case. However, the meteorological year used for the measurements was not the same as the year used in the simulation.

Work by Emery, Johnson, Heerwagen and Kippenhan (1981):

Window type(s):	Double pane, clear, reflective and heat absorbing glass
Window area(s):	25% of wall area
Shading device(s):	Exterior: aluminium louvered blinds, fixed overhangs, vertical fins Interior: venetian blinds, drapery Venetian blinds between panes
Climate(s):	United States (Seattle, Phoenix, New York)
Orientation(s):	South
Year/period(s):	1 typical year
Energy end-use(s):	Heating and cooling*
Research method(s):	Theoretical** (parametric study)
Result(s):	Guidelines: energy use and shading devices
Other:	*Also studied annual energy cost savings **Using the computer program *UWENSOL*

Emery, Johnson, Heerwagen & Kippenhan (1981) analysed the thermal performance of a perimeter office unit in a typical urban high rise office building located in Seattle, Phoenix and New York. The office was facing south and had a glazing area corresponding to 25% of the total facade area. The base case had double pane, clear glass windows. The authors observed the impact of adding a series of alternative shading devices (grey tinted glazing panes, heat-reflecting gold film on interior surface of exterior pane, aluminium louvred blind external to glazing, light-coloured operable venetian blinds used as interior shading, light-coloured operable venetian blinds set between the panes, fixed overhang—projecting 18" (46 cm) from external pane, fixed vertical fins on both sides of glazing—projecting 18" (46 cm) from pane, interior drapery of light colour and closed weave) on heat gain using the computer program *UWENSOL* developed at the University of Washington. Annual energy use and costs were analysed.

The study indicated climate dependent results. For New York, all the alternatives studied provided net benefits over a 20 year life duration in terms of energy cost savings. This was due mainly to a high unit cost of electricity. The cases with fixed overhangs and fins outside the window produced, however, very modest benefits. The highest benefits were obtained with 1) the heat-reflecting gold film on interior surface of exterior pane, 2) the grey tinted glazing and 3) the glazing with external aluminium louvred blinds. For Phoenix, six of the nine alternatives produced substantial net benefits in terms of energy cost savings. The electricity unit costs were lower than for New York but the annual consumption rates were higher. The best alternatives were the same as for New York but the case with external aluminium louvres was better than the grey tinted glazing. For Seattle, seven of the nine alternatives produced net benefits but they were marginal quantities compared with the benefits obtained for the other cities. This was explained by a low unit electricity cost and the mild climate. The best alternatives were 1) the grey tinted glazing, 2) the heat-reflecting gold film on interior surface of exterior pane, 3) the light-coloured operable venetian blind used as interior shading.

The results of the study were not verified against experiments. They were not validated against other computer simulations with other programs. It appears that the shading coefficients used were varied according to solar time and building latitude for the aluminium louvres and the exterior fixed devices but no detail of the calculation method used by the program is given in the article. No details were given regarding the management strategy for the blinds and louvres. Daylight and comfort were not considered. The main outcome of the study is that exterior fixed devices are poor performers compared with others, that special glazing are the best performers, and that venetian blinds and draperies are in between solutions. However, one would need to explain the blind management strategy employed to understand the results obtained.

Work by Brambley, Kennedy and Penner (1981):

Window type(s):	Not specified (assume single pane, clear glass)
Window area(s):	Many different
Shading device(s):	Sunscreens
Climate(s):	United States (San Diego)
Orientation(s):	All possible
Year/period(s):	1978, 1979
Energy end-use(s):	Cooling
Research method(s):	Experimental* (field study)
Result(s):	Information about effectiveness of sunscreens to lower cooling loads
Other:	*Recording energy use in single family residences equipped with the shading device

Brambley, Kennedy & Penner (1981) studied the performance of sunscreens for reducing air conditioning loads in single family residences through field studies in San Diego. They studied the electricity use of 66 houses in 1978 and 67 houses in 1979 before and after sunscreens were installed on windows. The study aimed to determine the conditions under which fenestration devices were used and the fractional reduction of cooling load achieved in residences where these devices were installed.

After verifying that sunscreens were used along with roller shades or curtains (for privacy) in 100% of the cases, the authors verified that adding sunscreens to windows with draperies reduced the cooling load by 23%. The total electricity savings were no more than 7.7% under clear sky conditions since the cooling load accounted only for about 1/3 of the total electricity use. In turn, the authors showed that owners of residences with air conditioning did modify significantly the thermostat settings and associated overall use of air conditioning (increasing the temperature) due to a net increase in energy prices during the survey period. Thus, the authors concluded that the data obtained for energy use were too strongly affected by changes in thermostats setting value to allow meaningful identification of an appropriate relation between energy use and sunscreens. They concluded that residences with installed sunscreens did not, on average, reduce electricity use significantly compared with similar households without sunscreens although there are reasons to believe that sunscreens contributed to improvement in comfort levels (but this was not investigated as such).

This study emphasised the importance of experimental verification of the impact of energy conservation measures on energy use and illustrated the difficulties that can be encountered in verifying the performance of marginally effective energy conservation devices. However, one should avoid drawing definite conclusions from the study since it was limited to one type of building. As pointed out by the authors, sunscreens may prove to be effective energy saving measures in buildings with high internal loads such as offices. The study was also limited to the cooling season. No survey was made in the winter period. This might have shown that sunscreens in place annually are responsible for increases in energy use in the winter and, thus, increases in annual energy use. The study also failed to account for the loss of daylighting. Finally, it should be mentioned that the study was limited to only one climatic zone, results might be different in warmer or colder climates.

Work by Halmos (1974):

Window type(s):	Double pane, clear and reflective glass
Window area(s):	Not specified
Shading device(s):	Interior venetian blinds Exterior solar protection (not specified which one)
Climate(s):	The Netherlands
Orientation(s):	East, south, west
Year/period(s):	April to September
Energy end-use(s):	Cooling
Research method(s):	Theoretical*
Result(s):	Guidelines: shading devices and energy use
Other:	*Using the *Carrier* calculation method

Using the *Carrier* method, Halmos (1974) calculated and compared the solar heat gain factors of a building with 3 different window systems in the climate of the Netherlands: 1) double pane, clear glass window with internal venetian blinds, 2) double pane, clear glass window with internal venetian blinds and reflective outer pane, 3) double pane, clear glass window with external solar protection. The author also compared the savings available for the different solar protection used.

The study showed that construction 3) had the smallest cooling load with construction 2) intermediate between construction 1) and 3). The solution with external solar protection had a much lower cooling load corresponding to almost 25% of the cooling load of construction 1). The south facade had a larger cooling load with the west being second.

The author failed to consider the period from November to March. The study completely focused on cooling loads and no account was taken of heat load and electricity use for lights. Only the south, west and east facades were considered in the study. No calculations were made for the north facade. No experimental verification of the calculations was performed throughout the study; the study is thus entirely theoretical.

Work by Dix and Lavan (1974):

Window type(s):	Single pane, clear glass
Window area(s):	1.20 m² (% of wall area not specified)
Shading device(s):	Interior: roller shades, venetian blinds, curtains
Climate(s):	United States (Midwest)*
Orientation(s):	Like south
Year/period(s):	1 typical year
Energy end-use(s):	Heating and cooling
Research method(s):	Experimental
Result(s):	Guidelines: thermal transmittance of shading devices and their impact on energy use
Other:	*Climate entirely simulated (temperature and solar radiation)

Through laboratory measurements, Dix & Lavan (1974) studied the effectiveness of roller shades hung inside a window (not sealed) in conserving energy in heated and cooled houses. They compared the effectiveness of these devices with that of standard venetian blinds and curtains inside a room. All devices were applied to a single pane clear glass window. The wall surrounding the test window was a normally insulated wall. The climate and radiation were entirely simulated to represent a typical climate of the Midwest of the United States.

The study indicated that the shading method along with the air flow patterns in the room were important factors in determining the heat flow reduction due to shading. In the summer, it was found that a window with light coloured opaque roller shade admitted 47-54% less heat in the room than an unshaded window considering both radiation (reduced by 63%) and conduction/convection processes (reduced by 25%). In contrast, venetian blinds reduced heat gain by 29% (closed) and 18% (45°) and light coloured drapery with white surface backing reduced heat gain by 33%. In the winter, the use of light coloured opaque roller shades reduced heat loss through the window by 24-31%. Typical venetian blinds reduced heat loss by only 6-7% depending on outside-inside temperature difference. The authors thus concluded that the use of window shades on typical residence windows in a moderate climate would reduce total energy costs by 8% during the heating season and by 21% during the cooling season.

In this study the authors based their energy saving calculations for the winter on the reduction of heat loss through a change in the conduction-convection processes caused by the installation of roller shades. No account was taken of solar radiation losses which would occur in the winter if the shade was pulled down during daytime. Assuming that blinds are pulled down during night time only, the energy savings would be much less than what the authors estimated. In the summer, the authors assumed that the blinds were pulled down all day—a situation very unlikely to happen unless the occupants would accept to have no contact with the exterior environment and to live on artificial lighting (increasing the cooling load) permanently. Although the study brings interesting knowledge about the insulating property of roller shades and other sorts of devices, the conditions in which substantial energy savings would be made are unrealistic.

3.2 Consideration of annual energy use including electricity for lights

Work by Sullivan, Lee and Selkowitz (1992):

Window type(s):	Double pane, clear, reflective and heat absorbing glass
Window area(s):	0, 15, 30, 50 and 70% of wall area
Shading device(s):	Interior: diffusing shades with different shading coefficients
Climate(s):	United States (Los Angeles)
Orientation(s):	North, east, south, west
Year/period(s):	Not specified (assume summer)
Energy end-use(s):	Cooling and lighting
Research method(s):	Theoretical* (parametric study)

Sullivan, Lee & Selkowitz (1992) developed a method based on the *solar aperture* (product of shading coefficient and window-to-wall ratio) and *effective daylight aperture* (product of visible transmittance and window-to-wall ratio) to analyse the annual cooling and lighting electricity use and peak demand associated with vary-

Result(s):	Guidelines in the form of nomographs relating energy use as a function of solar aperture and effective daylight aperture
Other:	*Using computer program *DOE-2*

ing fenestration and lighting strategies in commercial office buildings. Regression analysis procedures were used along with the data collected through a parametric study performed with the energy simulation program *DOE-2*. The office modelled was based on a four zone office building prototype in Los Angeles. It had a central core, perimeter offices and double pane windows. The windows' orientation, size, shading coefficient and visible transmittance and the lighting control strategy, the lighting power density and the desired illumination level were varied in the parametric study. Window-to-wall ratios tested were 0, 15, 30, 50 and 70%. Five glazing types with a range of U-values, shading coefficients and visible transmittance were simulated. An interior shading device was deployed when the quantity of transmitted solar radiation exceeded 94.5 W/m^2.

Results of the parametric study indicated that the electricity use and peak demand increased almost linearly with increasing window-to-wall ratio and solar apertures. The authors also found that perimeter electricity use for lights could be reduced by 73% using daylighting, taking down the total building electricity use for lights to about 26%. As the optimum performance relates to solar and effective daylighting aperture values that minimise energy use, the authors found that the tinted (green) (SC=0.41; Tvis=0.53) and a hypothetical, highly selective glazing (SC=0.30; Tvis=0.60) were the best performers. The authors developed nomographs relating energy use as a function of the effective daylight aperture and the solar aperture. These nomographs can be used to predict energy use or choose an appropriate glazing (calculating the solar aperture and the effective daylight aperture) which fits the "threshold" energy use required.

This study focused on the importance of considering lighting electricity use along with cooling load reductions when predicting the energy efficiency of different window choices. It also presented a good way of showing the relationships between energy use and the thermal-optical properties of the glazing and glazing area. Although it did not focus on shading strategies as such, the study showed that tinted (absorbing) or other hypothetical windows with high visible transmittance (in this case, over 50%) and low shading coefficient (under 0.40) are the most efficient solutions (among the ones tested) for the climate of Los Angeles, both in terms of reducing cooling loads and lighting electricity use. Apparently (but not mentioned in the article) the shading coefficient and transmittance values input in the model were not calculated according to the solar angle. Normal incident angle values were used instead. This could be a source of inaccuracy in the results. The study is only applicable to the climate of Los Angeles and to double pane windows. No strategy was developed for heating dominated climates. The effect of the U-value on glazing performance was not discussed either.

Work by Rundquist (1991a):

Window type(s):	Clear, heat absorbing and reflective glass
Window area(s):	From 0 to 80% of wall area
Shading device(s):	Exterior: overhangs, fins Interior: shade screens, vertical and horizontal axis blinds, automated louvers
Climate(s):	United States (Minneapolis**, New York***)
Orientation(s):	**North, east, south, west / ***South
Year/period(s):	June, March, December
Energy end-use(s):	Heating, cooling and lighting
Research method(s):	Theoretical*
Result(s):	Computer program *BEEM* (spreadsheet) + knowledge on shading devices and energy use
Other:	*Calculation based on ASHRAE methodology (1989); results validated with calculations with computer program *DOE-2*

Rundquist (1991a) developed a procedure embodied in a computer spreadsheet program (*BEEM*) to calculate the impact of window and shading configuration on a building's annual energy use and peak electricity demand. The program takes into account lighting, cooling and heating and interactions, including the use of daylighting. It treats different types of glazing, overhangs and fins, fixed shading devices which may be retracted in case of no sun or automatically adjusted. The program also gives daylight levels on the workplace. The calculation procedure for cooling impacts are based on ASHRAE methodologies (ASHRAE 1989). After presenting the program, the author described the results of a study made by running a number of cases with *BEEM* for the city of Minneapolis and New York to get indices for relative impacts of parameters and approach an optimum glass/shading device match. Calculations were made for June, March and December. Three types of building projections were treated for Minneapolis: overhangs, fins normal to the building and fins slanted 45° from normal (towards south on east and west exposures and towards east on north and south exposures). The calculations with *BEEM* were compared with calculations with *DOE-2*; results were in good agreement.

Some assumptions made during the study are worth mentioning. The fixed blinds were assumed to be adjusted to block all direct sunlight but were never opened beyond 45°. Automated louvres were assumed to be automatically opened as far as possible without admitting direct sunlight. However, horizontal axis blades were not opened beyond level i.e. up towards high sun angles (not to obstruct view). When there was no direct sun (overcast days) blades were placed normal to window. Workplace illumination was limited to the level required on the workplace.

The most important general demonstration of this study was that changing the input value (such as window size or shading coefficient) to increase daylighting to desired level always reduced total utility cost. The added lighting savings more than offset added cooling and heating costs. If lighting was not automatically controlled, however, cooling and heating costs increased proportionally with window size (or SC) and utility costs were minimised at window size = 0 m^2 (or SC = 0). North proved to be the most beneficial exposure because the glass without a shading device offered greater illumination relative to solar gain than glass with shading device (no shading assumed on the north facade at all times). The withdrawal of shades during the shaded half day on the east and west facade significantly increased utility savings because lighting savings were increased. Automated louvres provided significantly higher utility savings than either shade-screen or blinds especially for small window size.

For fixed blades in Minneapolis, vertical-axis had a slightly higher potential than horizontal-axis in terms of energy cost savings. For adjustable louvres, vertical-axis admitted more light for low profile angle but horizontal-axis provided greater workplace illumination at high profile angles and when no direct sun was present. For overhangs, it was found that projection ratios (distance to bottom of window) above 0.4 had only marginal effects on solar heat gain for south exposure. Larger projections were merely blocking a small additional portion of diffuse radiation. On the west exposure, the diminishing effect of larger projection ratios seen on the south exposure was not observed. Larger overhangs had the significant beneficial impact of shifting the time of peak solar gain to later in the day. Also, larger overhangs caused maximal utility savings to occur at large window size (because larger windows admit more daylight). For small windows, overhangs were net "losers" because reductions in lighting levels were too high. Slanted fins were more effective on west exposure because they blocked greater amounts of direct radiation after 1400 hours. For the south exposure, automated louvres had larger lighting savings especially for smaller window sizes. Shade-screens had significantly larger utility cost savings than blinds because exterior devices have a lower shading coefficient. For east exposure, vertical blade automated louvres did not offer as much utility savings as horizontal-blade louvres because the latter transmit more daylight.

For the New York city office building with only south facing windows of constant size, the author found that windows can actually provide utility savings relative to a solid wall and savings optimise at a definite window size and visible transmittance. It was shown that green tinted glass with a high transmittance shade was a near optimum choice when compared with dark glass/dense shade, reflective glass/dense shade and green tinted glass/dense shade options.

This work is truly interesting because it outlines the significance of daylighting for energy use and cost savings in office buildings. However, the results were only validated against results obtained with another program which uses the shading coefficient and U-value approach for solar heat gain factor calculations. Moreover, no experimental verification was made of the results. Although general comments are provided about the different results obtained, the author fails to define a shading strategy; the focus of the article is rather on the capabilities of *BEEM* and the type of results which may be obtained with this program rather than on providing useful recommendations for building designers. Finally, it should be said that the focus of the study is on utility cost savings rather than energy savings.

Work by Sullivan, Arasteh, Papamichael, Kim, Johnson, Selkowitz and McCluney (1987):

Window type(s):	Single, double and triple pane, clear, reflective, heat absorbing and low-e coated glass
Window area(s):	0, 15, 30, 45 and 60% of wall area
Shading device(s):	Interior: diffusing shade, venetian blinds
Climate(s):	United States (Madison, Lake Charles)
Orientation(s):	North, east, south, west
Year/period(s):	1 typical year
Energy end-use(s):	Heating, cooling and lighting***
Research method(s):	Theoretical* (parametric study) + Experimental**
Result(s):	Fenestration performance design tool
Other:	*Using computer program DOE-2 **Measurement of angular dependent solar and visual transmittance and reflectance of fenestration systems studied ***Also studied thermal and visual comfort and peak electric demand

Sullivan, Arasteh, Papamichael, Kim, Johnson, Selkowitz & Mc Cluney (1987) developed a fenestration performance design tool based on 5 performance indices (fuel use, electricity use, peak electric demand, thermal and visual comfort) to be used by builders, designers and architects. The numerical indices were derived from a large number of energy simulations of a typical building with the program *DOE-2*. Four types of glazing and two shading devices were combined in several ways so as to represent fenestration systems in use. The angle dependent solar and visible bi-directional transmittance and reflectance of fenestration systems were determined through direct measurement prior to the energy simulations using a scanning radiometer at the Lawrence Berkeley Laboratory and a mathematical procedure (*TRA*) developed by Papamichael and Winkelmann (1986). Heat transfer and light calculations were made with the programs *WINDOW-2.0* and *SUPERLITE*. Output of these two programs were used as input for *DOE-2*. The office modelled was a single storey four zones office with central core. Glazing area was varied parametrically from 0 to 15, 30, 45, and 60% of the wall area. Glazing types used were clear, bronze-tinted (absorbing), reflective, low emissivity coated and clear glass in single, double and triple pane arrangements. Shading devices tested were a diffusing shade and a venetian blind. Lighting was varied in two ways: varying lighting power densities and daylighting with continuous dimming controls for varying lighting levels. After the computer simulation, a regression analysis was performed and simplified algebraic expressions were derived.

Results of the study are simple algebraic expressions which permit calculation of a single numerical index relating the physical properties of a window (orientation, window size, window type, use of daylight, lighting power density, and lighting level) to its performance, in terms of energy use and comfort (visual and thermal). The numerical indicators developed are to be used as guides in evaluating and selecting alternative fenestration products and systems for various types of buildings and climates. This research is amongst the most original, useful and complete on the subject. Results are likely to be more accurate due to the method used which takes into account the angular dependence of the glazing's thermal-optical properties. The framework for this study can serve as a model for further studies on glazing or on solar shading devices. The development of simple, algebraic expressions for performance evaluation should also be remembered as a good, synthetic manner to express results of a parametric study.

Work by Winkelmann and Lokmanhekin (1985):

Window type(s):	Single and double pane, clear, heat absorbing, heat absorbing + reflective glass
Window area(s):	50% of wall area
Shading device(s):	Interior: operable blinds, fixed blinds Exterior: operable blinds
Climate(s):	United States (Miami, Los Angeles, Washington DC, Chicago)
Orientation(s):	North, east, south, west
Year/period(s):	1 typical year
Energy end-use(s):	Heating, cooling and lighting
Research method(s):	Theoretical* (parametric study)
Result(s):	Guidelines: shading devices and energy use
Other:	*Using computer program *DOE-2*

Winkelmann & Lokmanhekim (1985) used the program *DOE-2* to study the life-cycle cost (LCC) and annual energy use for a wide range of glazing and sun-control options in a typical 25-story office building with 50% glazing. The building was placed in four different climates: Miami, Los Angeles, Washington DC and Chicago. All facades were identical but two longer facades faced east and west. The window systems studied were: 1) clear glass with operable interior blinds, 2) clear glass with operable exterior blinds, 3) heat absorbing glass with and without interior blinds, 4) tinted glass with reflective coating. Both single and double pane options were studied. The authors also assessed the impact of daylighting for various sun-control options in the perimeter zone.

Results of the study indicated that adding exterior blinds reduced the solar heat gain by 74- 85%, depending on the city. Sun control options also contributed to an increase in the net heating load because of reduced solar gain but the authors did not specify by how much. Daylighting reduced energy use by 10-22% and was found to be cost effective in all four cities. Daylighting also raised the net heating load by reducing heat from lights but it was not mentioned in the article by how much. In all four cities, the alternative with the lowest first cost was single pane tinted glass without daylighting. In Miami and Los Angeles, the alternative with the lowest life cycle cost was single pane, clear glass with exterior blinds and daylighting. The alternative with the lowest life cycle cost in Washington was double pane, clear glass with exterior blinds and daylighting. In Chicago, it was double pane, clear glass with interior blinds and daylighting. Of all the alternatives considered, the lowest life-cycle cost and energy use were obtained with daylighting coupled with clear glazing and exterior sun control blinds.

This study shows the close relationship between the climate, the sun control option, the daylighting strategy, the glazing option chosen and the energy use. A range of glazing options were studied. However, internal loads from lighting input in the program were somewhat high compared with actual standards (approximately 3 times the value used in Europe). This might temper the impact of daylighting on energy use. On the other hand, the daylighting strategy consisted of switching off the electric light to 50% or 100% depending on the fenestration option and time of the year. This might have led to an underestimation of the impact of daylighting on energy use. For the cases with venetian blinds, the blinds were tilted to 45° in the cooling season. In the heating season, the blinds were fully closed at night and fully opened during the day. Higher energy savings would be achieved were the control options for the blinds more precise. As a whole, the study failed to assess the effect on energy use of window size or other sun control options such as solar screens, vertical interior blinds, blinds between panes or fixed external shading devices (overhangs, awnings, etc.). Nor did the study indicate sun control strategies as a function of facade orientation. Finally, it must be mentioned that no details were given in the article about the data input in the computer model. We suppose that a classical shading coefficient approach was used in the calculations.

3.3 Consideration of daylighting

Work by Brown (1993):

Window type(s):	Not specified (assume single pane, clear glass)
Window area(s):	Not specified
Shading device(s):	Interior: louvered screens, mini-blinds, horizontal louvers Exterior overhangs
Climate(s):	United States (San Diego)
Orientation(s):	North, east, south, west
Year/period(s):	During 4 stages of construction (not specified when); at 1200 and 1400 hours
Energy end-use(s):	Not included
Research method(s):	Experimental* (field study)
Result(s):	Information on daylighting levels
Other:	*Metering the daylighting levels

Through measurements of illumination levels in a building in different construction phases, Brown studied the impact of different shading devices and interior reflection on the performance of daylighting systems in one particular building (the new Pacific Beach Post Office). The shading devices used were standard louvred screens, mini-blinds, horizontal custom louvres and overhangs. No exterior shading devices were installed on the east and north facades.

It was found that before installing the shading devices high levels of illumination were recorded on west and south walls, creating glare problems (3500 lux). The installation of the horizontal louvres at 60° angle in the clerestories and windows solved this problem. The inclination of the horizontal slats to 30° contributed to reducing daylighting levels by around 60% compared with the bare case.

This study is not developed enough to allow any specific conclusion to be drawn about optimal shading strategies. Daylighting levels were only recorded at noon and 1400 hours. Results and observations cannot be generalised.

Work by Collett (1983):

Window type(s):	Double pane, clear glass with a single pane, clear glass window outside the main envelope system
Window area(s):	Not specified
Shading device(s):	Interior venetian blinds
Climate(s):	Not specified
Orientation(s):	Not specified
Year/period(s):	10 minutes
Energy end-use(s):	Not included
Research method(s):	Experimental* (field study)
Result(s):	Information about daylighting levels as a function of venetian blinds blade angle
Other:	*Real direct and diffuse daylighting conditions

Collett (1983) determined optimal venetian blind blade positions to obtain maximal illumination in direct sunlight and diffuse daylighting conditions. He developed curves expressing the sensitivity of daylight levels with respect to blade angle position and defined the relative daylight efficiency as a function of blade increment angle based upon empirical measurements. The small formula provided, based on the blade cut-off angle (angle between the blade and the horizon) concept allowed the determination of maximal and minimal blade angle depending on solar position.

Empirical measurements made by the author made it possible to verify that, in direct sunlight conditions, the relative daylighting efficiency for horizontal blinds (0° blade angle) is 65% when compared with a blind set at +20° cut-off angle (view upwards from inside). A blind set at -45° is only 24% efficient. In diffuse daylighting situations, 0° and -45° blade angles had a relative daylighting efficiency of 45% and 15% respectively compared with blinds oriented parallel to the brightest light source (+40°).

This study demonstrated the importance of precisely adjusting the blade angle position in order to obtain optimal levels of illumination in a room. However, for the direct sun lighting case, the author failed to define which was the sun angle. We should expect that one specific curve would exist for each sun position. Moreover, as pointed out by the author, only one aspect is regarded in this study; the choice of blade angle must also respond to visual and thermal comfort, view and privacy parameters. These imply a much more complex process to determine the optimal blade angle. It should also be said that one main limit of this study is that the basic building configuration with double envelope system is specific and complex.

It is hard to draw conclusions for simpler cases where a single building envelope system is used. The double envelope system is producing shadow. Finally, the measurements were only recorded in one single point. For all these reasons, no general conclusions, as a whole, can be drawn from this study.

Work by Bull (1953):

Window type(s):	Referred to as a simple "opening"
Window area(s):	83% of wall area
Shading device(s):	Interior: horizontal and vertical blinds
Climate(s):	Simulated overcast sky
Orientation(s):	Any
Year/period(s):	Not specified
Energy end-use(s):	Not included
Research method(s):	Experimental* (scale model)
Result(s):	Information about blinds slat angle and daylighting levels
Other:	*Measured lighting levels at 48 stations at desktop level

Through the use of a real scale model, Bull (1953) studied the effect of louvre arrangement in the window opening on the brightness and foot-candle levels inside a room. The author took measurements at 48 stations one foot apart at desktop height.

The study showed that horizontal louvres with 0° tilt reduced the average workplace foot-candles by 55-65% compared with the bare window case for the diffuse skies and by 79-87% for the clear skies. He also found that stations far removed from the window were much less affected by the introduction of louvres than stations next to the window. With 40° tilt, the average workplace foot-candle was reduced by 80-87% for the diffuse sky tests and by 91- 95% for the clear sky tests compared with the bare window. The author found that a 40° tilt was too extreme; it reduced light transmission through the window substantially. With the vertical louvres, the average foot-candles were reduced by 60-62% for the diffuse sky and by 75-90% for the clear sky tests compared with the bare case. The authors observed that the vertical slats offered greater variations along a line perpendicular to the window plane than horizontal slats; daylighting was more uniform in the room depth with horizontal louvres. The authors concluded that slightly tilted horizontal louvres distribute daylight better while vertical louvres control brightness in a better way.

This study is only valid for one latitude, results would differ according to the sun height and position at different hours of the day. The experimental setting using an artificial sky appeared to be a crude representation of real skies. It should give rise to some important inaccuracies in the results. However, the study can be considered as one of the first attempts to quantify daylight as a function of slat position for horizontal and vertical blinds.

4 Calculation methods to assess the performance of buildings equipped with shading devices and solar protective glazing

4.1 Algorithms to determine the geometry of shading devices

Work by Kensek, Noble, Schiler and Setiadarma (1996):

Kensek, Noble, Schiler & Setiadarma (1996) presented a computer program called *SHADING MASK* which is aimed at helping designers to understand the basic theory of solar control, generate sun path diagrams, design overhangs, side and eggcrate shading devices, calculate solar angles and shading masks and provide case studies of actual buildings.

Window type(s):	Any
Window area(s):	Any
Shading device(s):	Exterior fixed (awnings, overhangs, fins, etc.)
Climate(s):	Any
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Theoretical
Result(s):	Computer program *SHADING MASK**
Other:	*A didactic program aimed at determining geometry of exterior fixed shading devices

The program is essentially geometrical as it is only intended to provide information on the *shape* of optimal shading devices. It does not give any information on the solar heat gain factor associated with different shading devices.

Work by Bouchlaghem (1996):

Window type(s):	Any
Window area(s):	Any
Shading device(s):	Exterior fixed (awnings, overhangs, fins, etc.)
Climate(s):	Any
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Theoretical
Result(s):	Computer program*
Other:	*Aimed at determining the shape of shade

Bouchlaghem (1996) presented a small computer program based on a graphical method developed by *BRE* (Building Research Establishment), used to determine the shading created by exterior shading devices such as overhangs and awnings. The method is to some extent a replacement of the shading mask plus sun-path diagram “manual“ method used traditionally by architects to determine shapes of shades.

The program is only a means of defining the shape of the shade under a shading device at certain hours. It is purely geometrical. It does not say how much solar radiation enters the building and does not allow comparisons of energy use obtained when different shading alternatives are used.

Work by Etzion (1985):

Window type(s):	Any
Window area(s):	Any
Shading device(s):	Exterior fixed (awnings and overhangs)
Climate(s):	Any
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Theoretical
Result(s):	Algorithm*

Etzion (1985) presented a simple computer method based on the observation that morphologically, all shading devices (exterior awnings or overhangs) have the same shape and they only vary in their dimensions, more precisely in the co-ordinates of a key point called “M“ which deter-

Other:	*Simple algorithm based on "one point method" *Only includes calculation for the direct part of solar radiation

mines all other dimensions of the shading device. The determination of the single point "M" which is designated to shade exactly one lower corner of the window at any particular instant (defined by the designer) forms the basis of the algorithm presented by the author and simplifies geometrical calculations associated with exterior shading devices such as overhangs and awnings. The method presented can be used for the design of a shading device for a given sun position but it can also be utilised for the design of sun shades that will prevent the direct beam from hitting the window glazing during an extended period of time in the year. The advantage of the method is the small amount of computation needed to get accurate shape and dimensions of a shading device. Computation can be performed on an ordinary hand calculator or on a desktop computer. The only inputs needed for the computation are the width, height and orientation of the window and the solar position—azimuth and altitude.

It should be remembered that this method is only aimed at defining the proper geometry of shading devices. It does not take into consideration the energy use behind the shading or other aspects. It is a purely geometrical program aimed at helping a designer to define the optimal exterior shading device to protect specific parts of the window. However, the method is simple and could be used as a first step in an energy calculation program.

Work by Wagar (1984):

Window type(s):	Any
Window area(s):	Any
Shading device(s):	Trees
Climate(s):	Any
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Theoretical
Result(s):	Computer program *SUNPLOT**
Other:	*To determine appropriate position of trees around buildings; purely geometrical

Wagar (1984) developed a manual (based on sun-path surfaces) and computational (*SUNPLOT*) procedure for determining optimum placement of landscape vegetation in relation to windows. The author also indicated strategies to choose appropriate vegetation species resulting in the desired shading effect.

The procedures defined are useful only to determine the placement of shading but do not provide any indication of how much solar energy is transmitted inside the building.

4.2 Programs to calculate the amount of solar radiation entering a building

Work by Pfrommer, Lomas and Kupke (1996):

Window type(s):	Any
Window area(s):	Any
Shading device(s):	Interior and exterior venetian blinds
Climate(s):	Any
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included*
Research method(s):	Theoretical (analytical)**
Result(s):	Calculation procedure *GLSIM-BLIND****
Other:	*But prediction of solar gains can be used to estimate cooling/heating loads **Includes validation of the computer model with other computer models ***To model angle dependent solar radiation (direct and diffuse) transfers with venetian blinds and window systems

Pfrommer, Lomas & Kupke (1996) presented calculation procedures to model solar radiation transfers through horizontal slat type blinds outside and inside windows. The need to develop calculation procedures including slat type blinds and the different radiation components associated with them (transmitted, absorbed, direct, diffuse) on an hourly basis motivated the development of the computer procedure presented (*GLSIM-BLIND*). This program allows the study of any slat type arrangement and can be used to compare and optimise blind arrangements during the design phase. The program is based on analytical solutions rather than numerical or ray tracing techniques and can be solved on a PC. The radiation transmission is divided into 4 different paths: 1) the unshaded transmission of direct beam, 2) the direct-reflected beam from the slat surface, 3) the unshaded transmission of diffuse radiation, 4) the reflected diffuse radiation at the slat surface.

The model developed was verified through analytical investigation during the model development process. Also, inter-model comparisons were made using ray tracing programs like *RADIANCE*, for example. Pfrommer (1995) also made empirical validation of the model. The comparisons with empirical data predicted diffuse transmittance at each slat inclination in agreement with the computer model. The authors noted that calculation of the diffuse transmittance is the most complex part of the program so that the model should be pretty accurate for most situations. For combined blind and glazing, the comparison between *GLSIM-BLIND* and *RADIANCE* showed good agreement when the blind was inside while there were larger discrepancies when the blinds were outside the window. The authors suggested that further comparisons and data should be gathered and more validation analyses should be carried out before conclusions are drawn.

It was shown that *GLSIM-BLIND* is a good tool for predicting and describing solar gains when a blind shading system is installed outside or inside a window. This work is certainly amongst the most advanced on the subject and of great interest since it takes into account solar angle dependent optical properties of the blinds for both the direct and diffuse components of solar radiation. This work should be regarded as the most advanced tool for horizontal blind system calculations. Algorithms developed here could serve as a basis for the development of calculation methods for: 1) blinds between panes, 2) vertical blinds.

Work by Grau and Johnsen (1995):

Window type(s):	Any
Window area(s):	Any
Shading device(s):	Exterior fixed (awnings, overhangs, fins, etc.)
Climate(s):	Any
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Theoretical
Result(s):	Computer program *Xsun**

Grau & Johnsen (1995) presented the "polygon clipping method", a general principle allowing the calculation of the effect of shading objects on surfaces exposed to direct solar radiation. In this method, the obstructing objects are approximated by polygons in space, projected as seen from the

Other:	*Aimed at determining geometry of exterior fixed shading devices + produces files with solar fraction reaching the window for every hour

sun, at any given time of the year, onto the exposed surface of interest so that every sunlit region and the fully or partly shaded regions of the plane surface can be determined. The authors also developed a computer application called *Xsun* where the polygon clipping method has been implemented. This application allows for the determination of the shade's shape on windows located in a plane surface. The program also gives the solar fraction (*fsun*) reaching the window at specific hours. *Xsun* can be used for visual analysis of shading conditions at a specific day and hour of the year or to generate a file containing the values of the reduction factor *fsun* for each window and for every half-hour. This file may be imported and used in a thermal simulation program in order to obtain more precise predictions of direct solar gains.

The method presented can be useful. However, it does not take into account the effect of the shade on the diffuse radiation and reflections from the shade. Only shading of the direct component of solar radiation is taken into consideration. The program is mainly aimed at defining geometrical shapes of shades and does not allow calculations of the energy transfers inside the building containing the shades. It should be noted that this method is more complex than that presented by Etzion (1985) but allows a wider range of devices to be represented. However, Etzion's model may still be preferred because it makes possible accurate representation of most types of shading devices used in reality.

Work by Mc Cluney and Mills (1993) (see, also Mills and McCluney, 1993):

Window type(s):	Any
Window area(s):	Any
Shading device(s):	Interior vertical planar shade
Climate(s):	Any
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included*
Research method(s):	Theoretical**
Result(s):	Calculation procedure***

After defining the concepts of solar heat gain factor (SHGF) and shading coefficient (SC), McCluney & Mills (1993) identified the general problems relating to these concepts: 1) the lack of constancy of the shading

Other:	*But prediction of solar gains can be used to estimate cooling/ heating loads **Includes validation with measurements from ASHRAE ***For estimation of the effect of vertical planar interior shades on solar heat gain factor; no solar angle dependent values taken into account, only normal incidence

coefficient over different angles of incidence (especially for modern multi-pane and coated-pane windows), 2) the constancy of the reference glazing for the shading coefficient no longer valid (necessity to determine glazing performance under many different sky conditions, solar directions, spectral distributions of incident radiation, outside temperatures and wind speeds), 3) the effect of shading devices not taken into account in the shading coefficient concept (by definition, it only refers to glazing). The authors then present simple, preliminary calculation procedures for estimating the effect of vertical, planar, interior shades on the overall solar heat gain factor of a window system containing no other shading element. They then make a comparison between the calculated value of shade reflectance and shading coefficient and measurements of those parameters found in ASHRAE (1989, chapter 27, tables 25 and 28) and in a test report (DSET Laboratories, 1990) for some shades. The calculated and measured values agreed well.

A number of angle-dependent effects which can be significant with modern coated and multiple-pane window systems were neglected in this calculation procedure. The equations developed do not include the solar angle effects although the authors clearly explain that it is an important aspect to consider. They only represent normal incidence, and thus, only address one of the inadequacies mentioned about the shading coefficient and solar heat gain factor concepts (the lack of inclusion of shading devices effects). Also, a number of assumptions were made. One assumption was that all radiation absorbed is re-emitted as heat and the glazing is opaque to it. Another assumption is that the shade absorbs no heat from the room radiating back to the glazing, and finally, that radiation hitting the inside surface of the window from the shade is purely diffuse. As mentioned by the authors, more comparisons with measurements shall be made in the future to determine what are the implications of these assumptions.

Work by Prassard, Ballinger and Morrison (1992):

Discussion on issues relating to calculation methods for heat and radiation transfers through complex fenestration and shading systems

Prassard, Ballinger & Morrison (1992) present different advances in glazing (multiple glazing, insulated window systems with TIMS and evacuated glass units, spectrally and angular selective glazing) and frame technology and the new avant-garde window systems in development phase such as thermochromic, photochromic and electrochromic glass. The authors also outline the different shortfalls associated with calculations and test procedures for determining heat transfer and energy use associated with these types of glazing. According to them, frame and shading technologies are still misunderstood in their applications to computational models for temperature and energy calculations. They particularly insist on the many shortfalls in procedures such as ASHRAE heat transfer analysis, especially for advanced and novel glazing systems which exhibit dynamic behaviour and they express the need for developing a procedure with accurate and reliable measurement of properties under realistic conditions.

According to the authors, a number of effects in the ASHRAE procedure are not considered such as conductive heat transfer through the sash or other frame components, mass transfer effects caused by pressure difference and moisture difference across the window and other multiple order effects such as shading by shading systems or frame. Also the fact that the U-value and the shading coefficient are measured separately (U-value measured in the absence of solar radiation and shading coefficient measured in the absence of temperature difference) introduces a number of inaccuracies and problems. The U-value is not a constant since it is weakly dependent on the temperature and more strongly on the air velocities at the interior and exterior surfaces. The wrong assumption in the ASHRAE calculation that the wind speed at the glass surface is around 7 m/s could lead to errors of up to 30-40% for the U-value calculation of double pane windows, according to a number of cited authors (McCabe et al., 1984; Erhorn et al., 1987, in Prassard et al., 1992).

Problems with the shading coefficient are also mentioned. According to the authors, this number does not adequately describe the daily and seasonal variations that occur due to changing sun angles and diffuse to direct beam radiation. With the growing use of angular, spectrally selective and dynamically variable properties of glazing, the shading coefficient becomes inappropriate. New algorithms for correction of the solar heat gain coefficient such as Duffie & Beekman (1980, in Prassard et al., 1992) are still short of describing real behaviour, according to the authors. Moreover, laboratory based test procedures view small samples at normal angles of incidence: this can also be of little relevance in characterising performance because the glass is hardly ever applied in that position in real buildings. The authors conclude that much research is needed to develop measurement and calculation procedures that can accurately represent complex and advanced fenestration systems and their shading devices in energy performance calculation programs.

The authors agree fairly well with the ideas expressed by McCluney (1991) about the shading coefficient concept approach and the problems associated with it.

Work by McCluney (1991):

> Discussion on issues relating to calculation methods for heat and radiation transfers through complex fenestration and shading systems

McCluney (1991) wrote an important article where he explains why old concepts such as the shading coefficient are becoming inadequate for heat load calculations and why new or extended methods must be developed to replace those concepts. He also presents the different problems associated with the development of new calculation methods.

According to McCluney, the shading coefficient was devised as a convenient way to convert values of solar radiant heat gain through fenestration to equivalent values for a glazing system intended for the building being designed. However, for energy analyses including hourly building performance simulation calculations, the author explains that angle dependent values of the solar heat gain coefficient should be used instead. The single number shading coefficient is inappropriate for hourly building energy performance simulation calculations where the angle of incidence, the spectral distribution of the incident radiation and the outside wind speed adjacent to the window-wall vary continuously. Moreover, the author argues that some modern fenestration systems have strong variations both in spectral and angular distributions of their optical properties to meet energy and comfort goals. The author shows that the shading coefficient can no longer be used for complex spectrally selective multilayered fenestration systems. Also, he points out that questions of frame, mullions and edge effects are not addressed in the current definition of the shading coefficient. Moreover, because the modern definition of fenestration U-value now distinguishes centre-of-glass, edge and frame values, the author claims that it would be reasonable to expect the shading coefficient to include these differences as well. Finally, the author argues that for hourly calculations in changing environmental conditions, the solar heat gain coefficient of single pane, clear glass would vary (and thus the basis for estimating the shading coefficient of any other glass) and thus, the shading coefficient could not be used. This is another reason for the inadequacy of the shading coefficient: it depends on the variable properties of a fenestration different from the one it is intended to represent.

The author then argues that there is a need for methods that determine the angular dependence of solar radiant heat gain through many complex fenestration and shading systems for use in long term building energy performance calculations. Procedures have been developed by Reilly & Arasteh (1988) but these calculation methods neither include diffusely reflecting elements within the glazing nor interior or exterior shades and blinds. For more complicated fenestration systems, calculation methods are not generally available and measurements are required. However, the author points out that no published standard procedure exists regarding the method to measure solar radiant heat gain of fenestration systems. He concludes that, most likely, the solution will be to test fenestration components separately and use modern computer analysis methods to determine the relevant properties of component combinations making up a fenestration system. This calculation approach will be adequate for determining the direction-dependent solar heat gain coefficient of many fenestration products, including complex fenestration systems involving both specularly reflecting glazing and diffusely reflecting shading. It will, however, be complicated to deal with solar radiant heat gain properties of frame, mullions and other opaque window components and to include effects of shading devices. More work is needed in this area, according to Mc Cluney.

Work by Mc Cluney (1986, 1990):

Window type(s):	Any
Window area(s):	Any
Shading device(s):	Exterior awning (with and without side walls)
Climate(s):	Any
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included*
Research method(s):	Theoretical
Result(s):	Algorithm for calculation of shading by awning *AWNSHADE*
Other:	*But prediction of portion of solar radiation reaching the window can be helpful to estimate cooling/heating loads

Based on the work of Utzinger & Klein (1979), Sun (1975), Bekooy (1983) and Feuerstein (1979), Mc Cluney (1986, 1990) developed an algorithm for the calculation of the fraction of a window's area not shaded by an awning. Awnings with and without side walls of arbitrary inclination and cases of a horizontal overhang of arbitrary length and width at the top of the window can be handled by the algorithm. In the articles, the author derives the equations to calculate the effectiveness of awnings in shading windows from direct and diffuse radiation of arbitrary luminance and radiance distributions as well as for isotropic radiation.

As pointed out by the author, *DOE-2* uses a bar-polygon method converting various shading polygons in space into shadow polygons in the plane of the receiving surface window eliminating portions of shadows falling outside of the boundaries of interest on the receiving surface. Calculations are very complex and involved. The method presented by Mc Cluney is simpler and more straightforward. It calculates the unshaded fraction of a window shaded by an awning of arbitrary length and width and having side walls with lower edges making an arbitrary angle with respect to the horizontal. Awnings without side walls (Bahamas type) and simple overhangs can also be handled by the algorithm. The new algorithm is simpler and could easily be implemented in dynamic energy simulation programs to calculate the direct beam solar radiant and luminous flux incident upon the window for each hour of simulation.

Calculation of diffuse components assuming a uniform sky is also possible with the algorithm presented. The author notes that in many cases it is important to determine the effectiveness of shading devices in blocking diffuse sky radiation as well as direct beam radiation. (For example, in the study of shading devices by Mc Cluney & Chandra (1984) it was found that a lot of heat gain occurred through north facing windows. This was thought to be due to a fairly high radiant heat gain from the diffuse component. This points out the importance of the diffuse component in calculations of solar radiant heat gain through shaded windows.) The key to the algorithm development is the determination of the y and z co-ordinates of the projections of one particular key point onto the x = 0 plane. The method is similar to that presented by Etzion (1985).

The main limitation of the algorithm developed in 1986 was that it could not handle cases for which the shadow of the awning or overhang crosses the top horizontal edge of the window. This was a major limitation only for the case of awnings without side walls which are attached to the wall above the top of the window. Moreover, the absence of any treatment of ground-reflected radiation, the lack of an option for translucent shading devices were other important limits to the algorithm. These problems are overcome later as explained in an article published by the author (Mc Cluney, 1990). The new algorithm (*AWNSHADE*) is able to handle the case of shadows crossing the top edge of a window. Calculation of the portion of diffuse ground reflected radiation incident on the window that is not blocked by the awning has also been added to the program. This is done by assuming the ground to be an infinite half plane delivering uniform radiance from all directions to the window. To estimate what portion of the radiation coming from all of this half plane reaches the window by passing beneath the awning, a new set of "reversed" shading cases are described.

4.3 Algorithms to determine solar angle dependent properties of glazing

Work by Furler (1991):

Window type(s):	Homogeneous (uncoated) glass
Window area(s):	Any
Shading device(s):	Not included
Climate(s):	Any
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Theoretical
Result(s):	Algorithm to determine the solar angle dependent reflectance and transmittance of homogeneous glazing
Other:	

Furler (1991) developed an algorithm to determine the angular dependence of the transmittance and reflectance of homogeneous (uncoated) glazing layers given the reflectance and transmittance at normal incidence, the wavelength and the thickness of the glass. The algorithm can predict the glazing properties within 1.5% error for most clear, low-iron and absorbing glasses. This is a net improvement since—according to the author—existing approximations of the optical properties of glazing based on the angle dependent properties of 3 mm clear glass yield absolute errors of around 15% on transmittance or reflectance values. The author also shows that error for angles far from normal are even larger and that this can result in very inaccurate calculations of the energy performance of windows, given that most of the time during the day, the sun illuminates a window at angles of incidence greater than 45°.

Work by Furler is one step forward in improving calculation methods of energy flows through windows. This may be a very important part of the energy balance in a building. As demonstrated by the author, existing approximations of the optical properties of glazing material can lead to major misrepresentations of the solar gains through windows. Developments by Furler should be integrated into energy performance analysis tools.

5 Other work related to solar shading

Work by Sagelsdorff, Frank and Puntener (1984):

Window type(s):	Any
Window area(s):	20 m² (50% of floor area)
Shading device(s):	Any
Climate(s):	Switzerland
Orientation(s):	South
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Theoretical* (parametric study)
Result(s):	Nomograms to determine temperature fluctuations in a building with shading devices
Other:	*Using the computer program *HELIOS*

Sagelsdorff, Frank & Puntener (1984) present a nomogram for the rapid determination of the critical maximum indoor temperature in a building. The nomogram was constructed after the results of a parametric analysis using the energy simulation program *HELIOS*. The nomogram considers solar transmission factor, shading devices in place, window area, internal loads and the building mass. The simple nomogram is aimed at verifying whether a building has sufficient solar protection, compare different alternatives and be alerted of critical situations.

As mentioned by the authors, *HELIOS* has the disadvantages that: room geometry, window areas and orientations, thermal insulation values, air infiltration rates and internal heat sources are limited. Moreover, no heat absorbing glass may be used with this program. This means that some parameters cannot be represented in the nomogram. Regarding the nomogram itself, the main limitation is that the total transmission factor is to be estimated by the designer. This might be a complex process when shading devices and complex fenestration systems are involved. It should also be mentioned that the nomogram is only valid for the climate of Switzerland and gives only temperature values; cooling loads have to be estimated when the temperatures are obtained. The temperature values obtained are average values; they are based on the total transmission factor for one typical hour of the day. Finally, it should be mentioned that the nomogram developed has not been validated against experimental measurements and is, in any case, not useful for other climates or for dynamic energy performance simulations.

Work by Bornstein (1981):

Window type(s):	Any
Window area(s):	Any
Shading device(s):	Exterior fixed "egg-crate"
Climate(s):	Israel (desert)
Orientation(s):	South
Year/period(s):	1979
Energy end-use(s):	Not included
Research method(s):	Theoretical
Result(s):	Plans and sections of a shading device
Other:	

Bornstein (1981) presents the design of a fixed egg-crate shaped shading device which could be used in desert regions. This device is made to respond to all the solar angles when solar protection is needed. The device can thus offer protection for low morning summer sun as well as high noon and afternoon sun.

The article mainly deals with the geometry of this device. The device is intended for desert regions and could hardly be applied to cold regions because it blocks a large part of the daylighting. The author does not tell how much reduction in solar gain is achieved and what are the consequences of these reductions on energy use and comfort.

Work of Rubin, Collins and Tibbott (1978):

Window type(s):	Not specified
Window area(s):	29% of wall area
Shading device(s):	Interior venetian blinds
Climate(s):	United States (Gaithersburg, Maryland)
Orientation(s):	North, south
Year/period(s):	Not specified
Energy end-use(s):	Not included
Research method(s):	Experimental* (field study)

Rubin, Collins & Tibbott (1978) studied the way occupants of an office building manipulate interior venetian blinds in order to determine the feasibility of energy savings based on manual operation. The data obtained through repeated

Result(s):	Guidelines: management strategy of venetian blinds based on occupant behaviour
Other:	*Through photographs of the building from the exterior

photographs of the building from the exterior was based on the actual behaviour of occupants rather than on occupants response about their own behaviour. The aim of the study was to provide an explanation of the positioning of the venetian blind with respect to orientation, view and seasonal variables.

The study showed, most importantly, that people do position their blinds deliberately and do respond to external factors such as sunshine and view. The orientation was the most statistically significant factor affecting blind position with many more blinds completely pulled up on north than south side. More blinds were pulled down with slats open in February than in October and July (where blinds were drawn up). This was explained by lower sun positions. Also, blinds had a tendency to be more often drawn up when the view was open than when it was restricted. The authors explained this by an increased need for privacy when other buildings were in the view angle of the office. The study showed that the response to blind repositioning was relatively rapid, with more than 50% of the blinds being modified by the users by 0900 hours. However, once the blinds were modified at the beginning of the week (the researchers changed blind position during the weekend), they tended to be left in the same position afterwards, indicating that readjustment of blind position at intervals of days or hours in response to short term changes in environmental factors did not appear to be worth the effort for most people. In general, the authors noticed that people tended to tolerate more easily the completely open position (blinds pulled up) than the completely closed position (blinds pulled down, slats closed). This indicates that the positive functions of windows (daylight and view) outweigh the negative ones (overheating, lack of privacy). In general, this research shows that, under appropriate conditions, energy savings dependent on the activities of building occupants may be achieved. Especially, the use of daylighting appears a realistic objective since the study showed that people did adjust their blind in response to this factor in an approximate manner. The authors suggest that instruction on proper ways of manipulating blinds as a function of energy conservation might enhance the energy savings with manually manageable window shading systems.

The main limitation of this study was that the slat angle of the blinds was not monitored. This might have shown that although the occupants modified the blind height only once or twice a week, they modified the slat angle afterwards quite often. Only venetian blinds were studied, the response might be different for different types of shading devices. Moreover, there were no windows on east and west facade. Again, the response may be different on other orientations. Since no instructions about venetian blinds and energy savings were given to the occupants prior to the research, it was not possible to know if people would modify their habits as a consequence of energy saving considerations.

6 Related work

6.1 Window design and energy use

Work by Rossi and Visioli (1995):

Window type(s):	Not specified
Window area(s):	0 to 100% of wall area
Shading device(s):	None
Climate(s):	Italy (Venice, Rome, Trapani)
Orientation(s):	North, east, south, west
Year/period(s):	1 typical year
Energy end-use(s):	Heating, cooling and lighting
Research method(s):	Theoretical* (parametric study)
Result(s):	Guidelines: room orientation, floor area, configuration, window area and energy use
Other:	*Using the computer program *HEATLUX*; steady-state calculations

Through a parametric analysis using the program *HEATLUX*, Rossi & Visioli (1995) studied the primary energy use for heating, cooling and lighting in relation to some elements of the built environment such as: the thermo-physical and geometrical properties of windows and walls, the climate, the building layout, the area and shape of rooms and facade orientations. The authors simulated a series of typical building modules with a floor area of 60, 81, 108, and 144 m^2 and varying room configurations (although always rectangular). The window to depth of the room ratio was also varied and so was the orientation. The thermal resistance of the walls and the transmission value for the glazing (light and solar) were maintained constant over the entire process. There were no outdoor obstructions and no sun screens were used. The simulations were run for the climate of three Italian cities: Venice, Rome and Trapani.

The study showed that for the three cities, the total annual energy use changed with window dimension with a minimum value with window to floor area ratios between 17,5 and 22,5%. The authors also showed that an increase in window area caused a clear decrease in lighting energy and an increase in the cooling component while the heating component was mainly climate dependent. Since the energy use for lighting (45-85% of total) was a major part of the energy load, the authors concluded that an increase in window area in proportion to the floor area reduced the amount of energy use with minimum value when the window to floor area was around 17,5% for east and west orientations and 25% for south and north orientations. Overall, the energy use was greater for warmer climates and for east and west exposures. Most importantly, it was found that the total energy use as a function of the ratio to optimal window area did not differ much in relation to the area enclosed but changed, above all, in relation to the climate and to the configuration of the interior.

The program used to perform the calculations was using daily averages of total solar radiation on horizontal surfaces, sunshine index and average daily temperatures of outdoor air. This may have caused high levels of inaccuracy in the results. It may explain why optimum window to floor area ratios of 25% are obtained for both south and north orientations although these latter are asymmetrical with respect to the sun. Moreover, the results were never validated against experimental measurements. However, the fact that the room size and shape were varied is an interesting aspect of this study.

6.2 Effect of daylighting on energy use

Work by Andresen, Aschehoug and Thyholt (1995):

Window type(s):	Triple pane (light transmittance of 75%)
Window area(s):	1.65 m² (24% of wall area)
Shading device(s):	Exterior fixed: overhangs, fins
Climate(s):	Norway (Trondheim)
Orientation(s):	North, south
Year/period(s):	1 typical year
Energy end-use(s):	Heating, cooling and lighting
Research method(s):	Theoretical* + experimental**
Result(s):	Guidelines: energy use in offices with lighting dimming systems
Other:	*Using computer program *SUPERLITE, SUPERLINK* and *TSBI3* **Validation of the results with readings of the real building's energy use

Andresen, Aschehoug & Thyholt (1995) studied the energy use in an office building with dimming and on/off lighting control systems in Trondheim, Norway through computer simulations with *SUPERLITE*, *SUPERLINK* and *TSBI3*. With the on/off control system, the artificial lights were automatically turned off when the daylight level was sufficient in the office room (at 700 lux). With the dimming system, the artificial lights were progressively dimmed to a minimum of 10% of maximal power according to daylight levels. Results of the simulations were validated against readings of energy use in a real building.

The results of the simulations indicated that, for the north facing windows, the dimming control resulted in 40% reduction in lighting loads, 10% increase in heating loads, 60% reduction in cooling loads and 13% reduction in overall energy use. The on/off control system resulted in 5% reduction in lighting load, 1% increase in heating load, 19% reduction in cooling load and 2% reduction in overall energy use. For the south facing windows, the dimming system resulted in 48% reduction in lighting load, 11% increase in heating load, 70% reduction in cooling load and 18% reduction in overall energy use. The on/off system yielded 12% reduction in lighting load, 2% increase in heating load, 22% reduction in cooling load and 5% reduction in overall energy use. Thus the reduction in the number of switch-on hours for electric lighting not only leads to a reduction in energy use for lighting but, also, in a reduction in cooling demand and an increase in heating demand. It should be noted, however, that the absolute increase in kWh/yr for heating was greater than the absolute cooling energy reduction. In other words, cooling energy use accounts for a small share of total energy use in this climate compared with heating and lighting. Most of the savings obtained for overall energy use thus came from the savings in lighting energy. Comparison between calculated and measured values for lighting agreed well while large discrepancies were observed between calculated and measured energy use. This was partly explained by a too approximate definition of shading in the computer model, the use of different weather years and different locations for sensors.

This study gives good indications about the potential energy savings due to the use of daylighting in buildings located in extreme latitudes. It should be remembered that the study is limited to two orientations (south and north), one building type, one room size and one climate. Large discrepancies between measurements and calculated values of energy use demand further studies of the subject. Especially, this study showed the need to develop dynamic energy simulation programs able to handle shading systems and, also, to encourage the use of automated shading systems.

Work by Rundquist (1991b):

Window type(s):	Various “dark” glass
Window area(s):	1.22 m high continuous window (% of wall area not specified)
Shading device(s):	Various “shades”
Climate(s):	United States (New York)
Orientation(s):	North, east, south, west
Year/period(s):	1 typical year
Energy end-use(s):	Heating, cooling and lighting
Research method(s):	Theoretical*
Result(s):	Guidelines**: energy use in buildings with daylighting
Other:	*Using the computer program *BEEM* **Also includes the calculation of HVAC re-sizing and energy cost savings

Using the program *BEEM*, Rundquist (1991b) studied the interaction between the use of daylighting and energy use. The author calculated the impact of using a photo-sensor daylighting control system (dimming to 30%) on HVAC sizing, energy use and energy costs savings (expressed as payback periods).

The study showed that reduction of heat from lights due to daylighting can represent 10% downsizing in perimeter zone cooling and fans when HVAC is resized. He showed that typical payback periods for a photo-sensor lighting control system are between 1 and 5 years depending on window configuration. He also showed that it was possible to save 40% in lighting energy use over one year. The author demonstrated that the use of daylighting control systems has little impact on heating energy use compared with the impacts on cooling and lighting energy use because lighting reductions occur during sunny days. Added heating costs would be around 4%, not more. Finally, the author showed that the savings depended on the type of glazing and shading device used in the building. Low shading coefficient and transmittance glazing yielded moderate savings (less than 4%). Thus, the author suggested that higher transmittance glazing and higher shading coefficients be used with daylighting control systems. This strategy would permit a reduction of utility costs even if the cooling loads increase slightly due to an increase in solar gains. Lighter glazing with lighting controls sometimes reduces cooling more than dark glazing without control. The reduction of internal load from lights exceeds the increase in heat load from the sun.

This study underlines the importance of considering the lighting strategy along with window choice and shading strategy for a building. However, the focus of the study is on dollar savings rather than energy savings. The work of Rundquist does not allow one to identify clear strategies because only a few cases are presented. Although it can be assumed that the climate of reference in the study is somewhere in the United States, nothing definite is mentioned about it. Moreover, no experimental measurements are given to validate the computer simulations and no information are given about the computer program and the methodology used.

6.3 Daylighting calculation program

Work by Tsangrassoulis, Santamouris and Asimakopoulos (1996):

Window type(s):	Any
Window area(s):	Any
Shading device(s):	Can deal with a large variety of shading devices
Climate(s):	Any
Orientation(s):	Any
Year/period(s):	Any
Energy end-use(s):	Not included
Research method(s):	Theoretical + experimental*
Result(s):	Computer program for daylighting calculations**
Other:	*Model was validated experimentally **Based on daylight coefficient; treats both direct and diffuse radiation

Tsangrassoulis, Santamouris & Asimakopoulos (1996) developed a method based on *daylight coefficients* (illuminance at a point in the room / luminance of a patch of sky) to evaluate daylighting in the interior of a room. The method was compared with existing radiosity and ray-tracing methods and validated experimentally using measurements obtained in a *PASSYS* test-cell equipped with shading devices.

The main advantage of the method presented is that the inter-reflection calculation is carried out once for each zone and it does not have to be repeated if the sky luminance distribution changes. This approach allows hour by hour calculations of a building interior daylighting for a whole year rapidly without repetition of the inter-reflection calculation. Because the sky is treated as a number of point sources, the contribution of direct and reflected sunlight in the interior lighting can easily be assessed by adding, in the sky zone where the sun is located, an additional luminance equal to the normal solar illuminance divided by the solid angle of that zone. The method can also deal with a large variety of reflection models, innovative daylighting systems with complex geometry and complicated building geometry.

The method presented was compared with radiosity techniques. Results showed an average difference of 2.6% in illuminance with radiosity technique results. With *RADIANCE* (a backward ray-tracing method), differences were in the order of 1.9%. The authors proposed that the observed differences were due to the completely different calculation methods used in each case. However, the validation study showed that the daylight coefficient method might be an appropriate computer programming strategy to be used for the calculation of daylighting. This was emphasized with the experimental validation where it was demonstrated that the examined method predicted satisfactorily the internal illuminance at different points. This method for estimating daylighting inside buildings has a lot of potential, especially if it is to be used to calculate dynamically the illuminance levels in rooms for long periods of time in order to obtain data files for input in a dynamic energy simulation program.

7 Discussion and conclusion

This review primarily indicated the parameters which are relevant to the problem of shading in buildings. It showed that shading is related to energy use and comfort in the following way:

1) Shading affects energy use in buildings:

- Shading devices modify conduction-convection processes through the window thereby affecting heat losses through the envelope. This phenomenon influences heating and cooling loads.
- Shading reduces solar radiation reaching windows thereby lowering solar heat gains in buildings. This contributes to lower cooling loads but generally results in increased heating loads.
- Shading affects daylighting availability in buildings. When dimming systems are used to lower artificial lighting levels if sufficient daylighting levels are measured, shading can thus indirectly affect electricity use for lights. Lower artificial lighting levels are also connected with higher heating and lower cooling loads since light is a source of internal heat gain.

2) Shading affects occupants' comfort:

- Shading devices modify visual comfort by changing illuminance levels in rooms.
- Shading devices affect thermal comfort primarily because they modify the amount of solar radiation entering a building. Solar radiation can be associated with air or surface temperature fluctuations.

Shading devices also affect comfort by allowing different levels of privacy in a room and by modifying air flow patterns through the windows in naturally ventilated buildings. These issues are, however, not discussed in detail in this literature review.

The review indicated that an optimal shading strategy to achieve efficient use of energy necessarily depends upon the following factors:

- the physical (thermal and optical) properties of shading devices
- the management strategy used for the devices
- the climate where the building is erected
- the daylighting/lighting strategy in this building

High levels of visual and thermal comfort depend on these issues as well as others such as the occupants' activity, seating position, etc.

In order to develop good shading strategies or to assess the impact of a shading device on energy use, comfort or both, computer simulation tools must be developed. This review showed that development of accurate calculation tools will require the following:

1) Development of databases with physical properties of shading devices:

- The impact of shading devices on thermal losses through multiple pane (2, 3, 4) windows needs to be assessed.
- Thermal properties of shading devices need to be estimated in close-to-real conditions i.e. when solar radiation, temperature, wind and humidity fluctuations occur.
- Optical properties for different sun angles need to be measured for each individual type of device.
- Standard measurement procedures to assess physical properties need to be developed.

2) Development of mathematical models to assess energy use and comfort:

- Mathematical models for venetian blinds and awnings are fairly advanced. Recent models allow dynamic calculations of heat/radiation flows through venetian blinds and awnings taking into consideration varying sun angles and diffuse/direct components of solar radiation. Validation work is needed in this area.
- Mathematical models for roller shades, vertical blinds, and all other kinds of shades need further development in order to describe accurately solar angle-dependent direct, diffuse and ground-reflected radiation flows.
- These models for shading devices need to be connected with global energy performance simulation programs which calculate an entire building's energy use.
- Calculation methods of accurate, hour-by-hour daylighting levels in rooms are fairly advanced but need to be connected with energy performance tools to allow assessments of energy use in daylit buildings (where artificial lights are dimmed).
- Glare and comfort indexes to suggest best solutions in terms of comfort as well as energy need to be integrated in energy simulation tools.

Although the issue of shading in buildings has been studied extensively as exemplified by the amount of available literature on the subject, there is room for work on the development of databases of physical properties of shading devices and computer programs to assess energy use and comfort in shaded buildings. These tools will ultimately allow building consultants to choose preferred solutions from a set of alternatives and to devise optimal shading strategies for each specific climate and building type.

Summary

Since the 40's, research related to solar shading and buildings has focused on three main issues:

1) The properties (thermal and optical) of solar protective glazing and shading devices
2) The effect of solar shading on energy use and daylighting in buildings
3) The calculation methods to assess the performance of buildings equipped with shading devices or solar protective glazing.

Properties of solar protective glazing and shading devices

Thermal transmittance

A large number of studies aimed at quantifying the reduction in heat flow through windows when various types of shading devices are used and conditions of no solar radiation prevail have been made in the 70's and 80's. These studies showed that shading devices affect heat flow through windows significantly, especially when installed on single pane, clear glass windows. The thermal resistance of the window-shade system is greatly improved if the shading device traps an air layer next to the window glass. Sealing edges of the shade to the window and using airtight fabrics are ways to improve the window-shade system's thermal resistance.

The amount of heat flow reduction obtained through tests with various shading systems varies according to the type of shading device tested, the experimental conditions and the type and size of window used in the experiment. When shades are applied to single pane, clear glass windows, Lund (1957) found that interior aluminium foil shades on cloth reduce heat losses by 58%. ASHRAE (1972) suggested that venetian blinds, draperies and roller shades reduce the U-value of the window (hence the heat losses) by at least 25%. Grasso et al. (1990) found that draperies improve the thermal resistance of windows by 40% (reducing heat losses by 30%). Horridge et al. (1983) found that most shading devices (venetian blinds, translucent rollers, vertical blinds, opaque roller shades and drapery liners) improve the window's thermal resistance by up to 70% (reducing heat losses by 41%). Grasso & Buchanan (1979) showed that roller shade systems reduce heat losses by 25-30% while metallic coated roller shades reduce the losses by 45%. Finally, work at the Department of Energy (ETSU, 1990) demonstrated that thermal effects of net curtains or venetian blinds are negligible while light curtains reduce heat losses by 20% and heavy curtains by 40%. Lunde & Lindley (1988) found that roller shades, roman shades and films reduce heat losses by up to 50% when sealed to double pane, clear glass windows. Few other studies attempted to assess the heat loss reduction provided by shading devices coupled with double pane windows. The author is not aware of any existing studies which assess the thermal transmittance of triple pane windows equipped with shading devices.

In summary, most authors agree that venetian blinds, draperies and roller shades inside single pane, clear glass windows reduce heat losses by 25-40%. Metallic coated shades inside windows reduce heat losses by 45-58% depending on the material and mounting method used.

Solar transmittance

Since the end of the 50's, a number of researchers have attempted to define optical properties of shades. The optical properties have been expressed in terms of solar transmittance and reflectance values, solar heat gain factor or shading coefficient. These studies do not usually permit specific conclusions about annual energy use in buildings but they indicate, in a general manner, "how well a shade shades".

Although they express the capacity of shading devices or solar protective glass to cut out solar radiation, they do not indicate optimal shading strategies for any particular climate.

Olgyay (1963) classified shading devices according to their shading coefficient from the least to the most effective in reducing solar radiation as follows: 1) venetian blinds, 2) roller shades, 3) insulating curtains, 4) outside shading screen, 5) outside metallic blind, 6) coating on glazing surface, 7) trees, 8) outside awning, 9) outside fixed shading device, 10) outside movable shading device. According to this author, exterior shading devices are more effective by 30-35% in reducing solar radiation entering a building than interior devices which can only reflect a small part of the radiation and release heat absorbed back into the building. Heat absorbing panes and devices set between panes are about 15% more effective than are interior shading devices (Architect's Journal, 1976). Also, Olgyay (1963) mentions that off-white colours usually provide more effective shading than dark colours because they reflect more radiation. Steemers (1989) estimated that exterior fixed overhangs are more effective than vertical fins and egg-crate devices in reducing solar radiation on south, east and west facades although the difference between overhangs and fins is small for east and west facades. Also, vertical fins are better on the north facade than overhangs and egg-crate devices. Prismatic panes have a solar transmittance of 10% in the summer and 90% in the winter with direct sun and a transmittance of 70% for diffuse radiation (Christoffers, 1996). Finally, Hoyano (1985) found that vegetal vine sunscreens have a weak solar transmittance of 25%.

Effect of solar shading on energy use and daylighting in buildings

A large number of parametric studies of solar shading devices and energy use have been made since the development of energy performance computer programs. The relationship between shading and energy use has also been studied through experiments with the first work on the subject by Peebles (1940). Researchers first paid attention to the relationship between cooling loads and solar protection. Then, the impact of shading devices on heating loads and annual energy use was assessed. Since the middle of the 80's, however, the development of dimming systems allowing daylighting to replace artificial lighting in buildings means that the impact of shading on daylighting levels and, hence, electricity use for lights must be considered along with heating and cooling loads.

Considering cooling and/or heating loads

Studies of the effect of solar protection on heating and cooling loads show that shading strategies are climate dependent. While most authors agree that solar protection does reduce energy use for cooling and tends to increase heating loads, few of them agree on how much energy can be saved and what is the best shading strategy overall.

Shading devices lower the energy use for cooling. Harkness (1988) showed that exterior precast concrete overhangs and fins reduce the cooling load by at least 50% in Brisbane, Australia. Brambley et al. (1981) showed that sunscreens reduce cooling loads by 23% in San Diego. Halmos (1974) demonstrated that external shading devices installed on double pane, clear glass windows reduce the cooling load by 75%.

A number of researchers showed that most shading devices contribute to increases in energy use for heating while they reduce the cooling load. Bilgen (1994) found that automated venetian blinds between panes increase the heating load by 4-6% and reduce the cooling load by 69-89% in Montreal. Treado et al. (1984) showed that various types of shading devices increase the heating load while the cooling load is reduced; the net energy savings only occur if the reduction in cooling energy use exceeds the increase in heating energy use. In general, it was demonstrated that cooling loads are reduced with decreasing shading coefficient (better shade) while the opposite was observed for the heating load. Higher shading coefficient (poor shade) results in lower heating loads. According to Treado et al. (1984), as the respective shares of total energy use due to heating and cooling loads depend on the climate where the building is erected, so does the shading strategy. In an earlier study, Treado et al. (1983) also found that window films do not result in annual energy savings in heating dominated climates. Films generally contribute to larger increases in heating loads than to reductions of energy use for cooling. Emery et al. (1981) also found that shading strategies are strongly climate dependent. According to them, fixed overhangs and fins yield a modest reduction in energy use and the best shading strategies in three American cities are reflective glazing, heat absorbing glazing and glazing with exterior aluminium louvres. Hunn et al. (1990, 1993) tested a variety of interior and exterior shading devices in a heating dominated climate and found that a higher performance is obtained with interior shading devices (as opposed to exterior fixed) when energy cost and use and peak demand reduction are analysed. Interior devices, which shade the entire glass while providing additional insulation to the window can save as much as 30% energy for cooling, resulting in annual energy savings of the order of 10% for offices. These authors (1990, 1993) also showed that external shading devices are often net energy losers because they reduce useful solar gains during the winter. Heat absorbing glass, reflective glass, annual solar screens and overhangs plus fins almost always result in increased annual energy use. These observations confirm results obtained by Pletzer et al. (1988). Mc Cluney & Chandra (in Germer, 1984) found the opposite for the climate of Florida: exterior devices (overhangs, awnings, window screens) are the best energy savers while tinted glass is the least energy efficient solution.

Few authors showed that shading devices can reduce the energy use for both heating and cooling seasons. Cho et al. (1995) showed that internal venetian blinds reduce heating loads by 5% and cooling loads by about 30% in South Korea. However, the reduction in heating load was due to increased thermal insulation provided by the shading device at night. During the day, the devices were net energy losers. Rheault & Bilgen (1987a, 1987b) demonstrated that automated venetian blind systems between panes can reduce heating loads by 30-70% and cooling loads by 91% in Montreal. However, results from this study were obtained through calculations with a computer program which was not validated experimentally.

Considering annual energy use including electricity for lights

It is a fact that using dimming systems to replace artificial light by natural light reduces the energy use for lighting. Sullivan et al. (1992) showed that perimeter electricity use for lighting is reduced by 73% through the use of daylighting.

Authors disagree, however, on the benefits of using daylighting to reduce overall energy use (lighting, cooling and heating). Andresen et al. (1995) showed that for south facing windows in Trondheim, the use of daylighting results in 48% reduction in lighting load, 11% increase in heating loads and 70% reduction in cooling loads. Winkelmann & Lokmanhekin (1985) demonstrated that daylighting reduces the overall energy use by 10-22% and is cost effective in Miami, Los Angeles, Washington DC, and Chicago. The lowest energy use option is obtained when daylighting is coupled with clear glazing and external sun-control blinds for all the cities studied. Rundquist (1991) showed that, in Minneapolis and New York, increasing daylighting levels (through increases in window-to-wall ratio or shading coefficient) always reduces utility costs. He showed that when daylighting is used, windows provide utility savings relative to a solid wall. When daylighting is not used, increasing the window-to-wall ratio and the shading coefficient always leads to increased cooling and heating loads. This contradicts findings by Sullivan et al. (1992) who demonstrated that electricity use (cooling and lighting) and peak demand are almost linearly increased with increasing window-to-wall ratio and solar aperture (product of the shading coefficient and the window-to-wall ratio) in Los Angeles, when daylighting is used.

In short, the shading strategy to adopt when daylighting is used has not been clarified yet and is a complex problem. Although most researches demonstrate that daylighting use yields lower annual energy use, more work is needed in this area to define appropriate shading and daylighting control strategies that make an efficient use of energy.

Shading devices and daylighting

Few studies have looked at the problem of solar protection and daylighting levels in rooms. Collett (1983) and Bull (1953) attempted to determine optimal blind blade angle arrangement as a function of illuminance levels in rooms. Results obtained by these authors cannot be compared because experimental settings and measurement points and conditions were too different. No specific conclusion can be drawn from the work by Brown (1993) who attempted to measure illuminance levels when daylighting and shading systems were installed in a real building during different stages of construction.

Calculation methods to assess the performance of buildings equipped with shading devices and solar protective glazing

Geometric models

Since the beginning of the 80's, a number of computer programs have been developed to determine accurately the optimal shape of exterior shading devices—such as awnings and overhangs—with respect to the sun under clear sky conditions. Bouchlaghem (1996), Kensek et al. (1996), Etzion (1985), and Wagar (1984) all contributed to provide such models which are mainly concerned with the geometry of shading devices and do not contain energy simulation algorithms to assess the performance of the devices in terms of energy use.

Programs to calculate the amount of solar radiation entering a building

Parallel to this work, dynamic (hour by hour) computer programs calculating the radiative energy flows through solar protective glass and shading devices have been developed since the middle of the 80's. One of the most important contributions is the work by Pfrommer et al. (1996) who developed a dynamic model to calculate radiation flows through venetian blinds located outside and inside windows, taking into account both the diffuse and direct part of solar radiation and varying solar angles. Also, Cho et al. (1995) developed a calculation module to connect with *TRNSYS* (a dynamic energy simulation program) for the assessment of the effect of interior venetian blinds on energy use. Grau & Johnsen (1995) developed an algorithm to determine the solar reduction factor when exterior fixed shading devices are used. However, the program does not calculate reductions of diffuse radiation entering the building. Mc Cluney & Mills (1993) provided an algorithm to model radiative energy flows when vertical planar shades are used on the interior side of a window. This algorithm does not take into account solar angle dependent optical properties of shading devices. Mc Cluney (1986, 1990) also provided a program calculating the reduction of the solar factor (direct, diffuse and ground reflected) when awnings are used.

Finally, texts by McCluney (1991) and Prassard et al. (1992) about calculation methods associated with shading and energy use should be mentioned because these authors identified some of the most important problems left to be solved in energy calculation models: the replacement of the shading coefficient concept by appropriate solar angle dependent properties of window-shade systems and the accurate representation of radiative and heat transfers through complex fenestration systems coupled with shading devices. Algorithms by Furler (1991), Papamichael & Winkelmann (1986) and Pfrommer (1995) to determine solar angle dependent optical properties of glazing are promising advances in this field. These developments will eventually contribute to improve the accuracy of dynamic energy calculation programs for buildings equipped with complex fenestration and shading systems.

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