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Practical use of new visual discomfort probability index in the control strategy for solar shading devices

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SUMMARY

The present study describes the practical use of a new index for visual discomfort probability (VDP) implemented in the building simulation software BSim for evaluation of the impact of the control strategy on visual comfort and energy consumption. The VDP index describes the fraction of persons that are likely to be disturbed by glare under a given daylight situation. As a measure of glare, the vertical illuminance at eye level was used, since previous research has shown good correlation between eye illuminance and user’s response regarding glare perception. The evaluation of different simulated solar shading control strategies showed that even the most advanced existing shading control system (cut-off strategy) does not meet the users' need for protection against glare. By using control strategies based on the visual comfort criteria, there was a great potential for improvement of the indoor environment. The results also showed that improving the visual environment had small costs in energy for lighting and heating.

KEYWORDS

Indoor Air 2008, Solar shading devices, Glare, Visual discomfort, Daylight utilisation

INTRODUCTION

Based on the experience from the studies of user interaction with different shading devices and laboratory studies at Fraunhofer Institute Freiburg, ISE, and the Danish Building Research Institute, SBi (Wienold & Christoffersen, 2006, 2008), new models for control of solar shading devices was implemented in the BSim software package. The impact of different shading control strategies in an office building with respect to: minimum glare and minimum overheating over the working hours, as well as minimum total energy demand was assessed by simulations for two climatic conditions (North and South of Europe). The objectives of this study was to investigate:

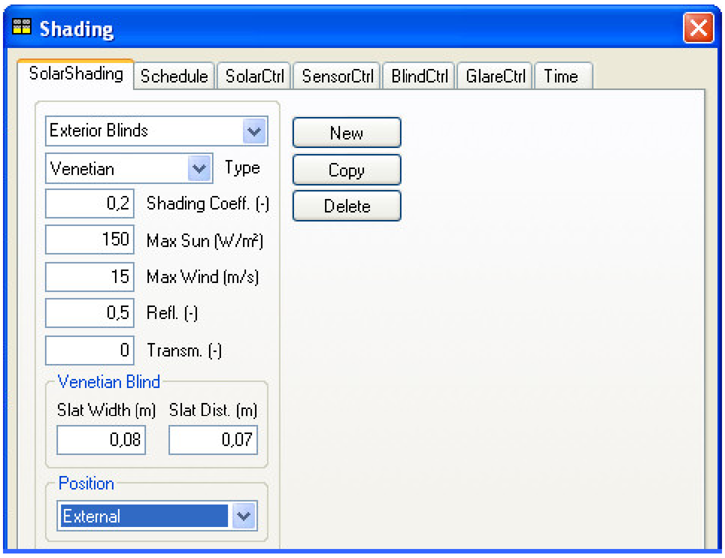
- if conventional shading control strategies meet the users' needs for preventing glare and overheating, and
- if new control strategies based on visual comfort will increase the overall energy demand

METHODS

Three new control strategies were implemented in BSim. The solar shading device is described by a few physical parameters as shown in figure 1. The parameters used depend on the type of control system. In this case the shading device is an external Venetian blind. In addition to the existing control strategy (called Solar Control) three new control models were implemented in BSim. The following control strategies for the blinds were simulated in order to assess the impact on visual and thermal comfort as well as on energy consumption:

- No blinds
- Blinds down and fixed slat angle when there is direct sun

- Cut-off angle control which puts the blinds down when the solar irradiation exceeds a chosen limit and tilts the blind slats in a position that cuts off all direct sun
- Glare control strategy to keep the visual discomfort probability due to glare below two levels: 30% and 70%.



Exterior Blinds
Venetian Type
0,2 Shading Coeff. (-)
150 Max Sun (W/m²)
15 Max Wind (m/s)
0,5 Refl. (-)
0 Transm. (-)

Venetian Blind
Slat Width (m) 0,08
Slat Dist. (m) 0,07

Position
External

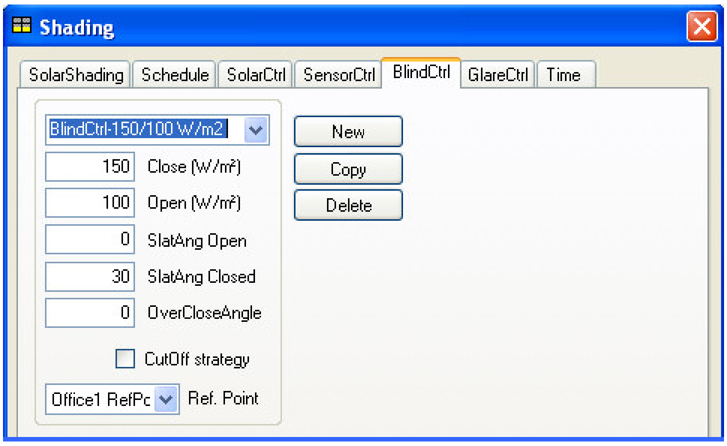
Figure 1. Shading device definition. The parameters used depend on the type of control system. In this case the shading device is a Venetian blind with slat width 8 cm and slat distance 7 cm. The light reflectance of the slats is 0.5. The dialogue also defines the look-up table where the light distribution in the office has been pre-calculated for any position of the blinds, i.e. height/retraction and angle.

No blind case

The "No blinds" case was simply defined as a solar shading that would be used when the solar irradiation on the façade exceeded 1000 W/m2, which means that it would never come into function.

Fixed blind slat angle strategy

In the fixed angle strategy, the user defines the thresholds for activating and de-activating the blinds by the values of solar radiation through the window. In BSim a new dialogue for "Blind control" was implemented, see figure 2.



BlindCtrl-150/100 W/m2
150 Close (W/m²)
100 Open (W/m²)
0 SlatAng Open
30 SlatAng Closed
0 OverCloseAngle
☐ CutOff strategy
Office1 RefPc Ref. Point

Figure 2. Definition of control strategy for shading devices with slats or lamellas. The user can define at which value of solar radiation through the window the shading is activated (closed). One variant of the blind control strategy is the cut-off strategy.

When the blinds are activated, the slats are tilted to the angle defined by the user. It is possible to define any number of different strategies over the year, which means, for instance, that the tilt angle can be defined differently for different times of the year and of the day. In this case the threshold values of solar radiation were set to 150 W/m^2 and 100 W/m^2, and a fixed slat angle of 30° was chosen.

Cut-off angle strategy

A new model for "cut-off" strategy was implemented in BSim. In practice this is probably one of the most advanced existing shading control strategies, since the control system must keep track of the "sun's position", and tilt the slats in an angle that just cuts off the direct sun, hence the expression "cut-off angle", as illustrated in figure 3 (left). The cut-off angle can be expressed by the profile angle and the ratio of slat distance and slat width:

$$\beta_c = \arctan\left\{ \frac{\tan\theta - d \cdot \sqrt{1 + \tan^2\theta - d^2}}{d^2 - 1} \right\} \tag{1}$$

θ is the profile angle determined from the (solar - window) azimuth and solar height
d is the ratio of the slat distance over slat width.

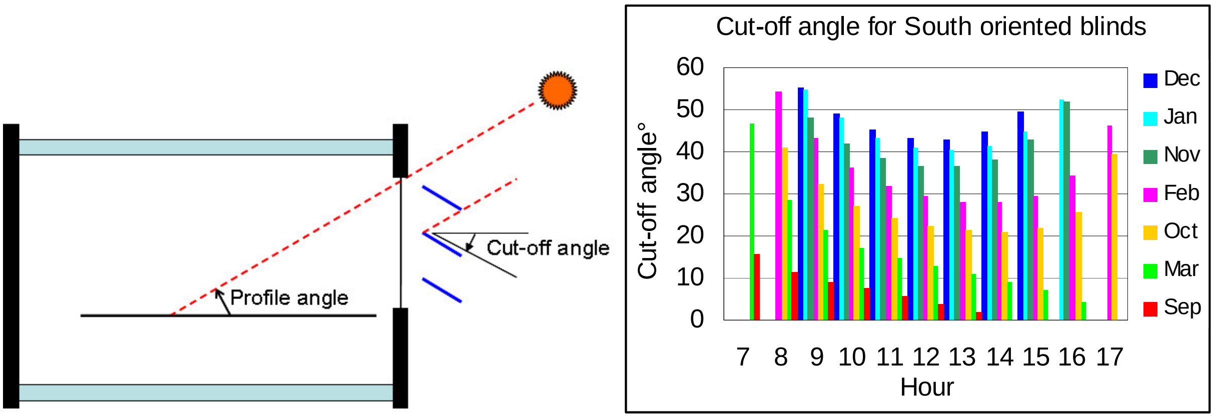
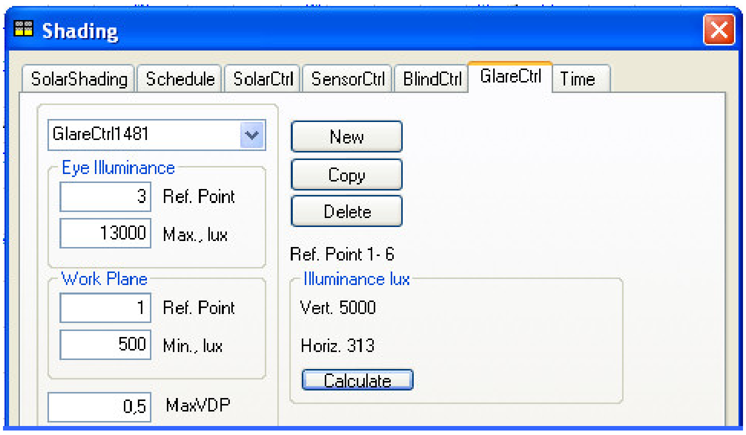


Figure 3. Left: Illustration of the cut-off angle, which is the angle of the slats, measured from horizontal, that just prevent direct solar radiation from penetrating the blinds. Right: Typical cut-off angle for South facing facade, in this case for Copenhagen. For all hours of the months not shown the cut-off angle is 0, which means that no direct sun will pass through a blind with horizontal slats.

In the "Blind control" dialogue the strategy is chosen by ticking in the "Cut-Off strategy" field, see figure 2. Then for each half hour of the simulation where the blind is activated BSim calculates the critical angle. It is possible to add an "over-close angle" in order to limit the number of changes of the blind position over the day.

Glare control strategy

The glare control strategy is actually a strategy that aims at minimising the visual discomfort due to glare, but at the same time aims at maintaining a certain daylight level on the work plane (the desk). The two criteria of visual discomfort have been implemented in BSim, as described in the dialogue in figure 4.



GlareCtrl1481

Eye Illuminance
3 Ref. Point
13000 Max., lux

Work Plane
1 Ref. Point
500 Min., lux

0.5 MaxVDP

Ref. Point 1-6

Illuminance lux
Vert. 5000
Horiz. 313

Figure 4. BSim dialogue for definition of "Glare control". In the simulations pre-calculated values of the illuminances in the reference points were used. The dialogue is prepared for direct calculation in BSim by defining any number of different reference points of the room.

Visual discomfort probability due to high illuminances

For a chosen reference point the illuminance is calculated for each hour and for the given position of the blinds. In this case the values pre-calculated by ISE using the Radiance software (Ward, 1998) were used. The reference point was on a vertical plane at the eye position of a user in the office. In BSim the glare criterion is as a simplified version of the algorithm developed by Wienold & Christoffersen (2006, 2008), (*VGDP*) see figure 5 (right):

$$\begin{aligned} &if\ \ E_v < 500 : VDP = VLDP_{\min} \\ &if\ \ E_v > 13700 : VDP = 1.0 \\ &else\ \ VDP = 6 \cdot 10^{-5} \cdot E_v + 0.17 \end{aligned} \tag{2}$$

VDP is the general index of visual discomfort probability
$VLDP_{min}$ is the lowest achievable value of the discomfort index at low illuminance (0.2)
E_v is the illuminance on the vertical plane at eye position

In the simulation two different values of VDP (glare) were chosen: VDP < 0.3, which corresponds to an illuminance level at eye position < 1667 lux, and VDP < 0.7, which corresponds to an illuminance level at eye position < 8333 lux

Visual discomfort probability because of too little (day-)light on the desk

In order to maintain a certain illuminance level on the desk, the blind is only closed to the position that just keeps the glare value below the desired level. The starting height is chosen as that of the previous half hour. So when BSim find the slat angle that fulfils the criteria, it checks if the blind can be raised to a higher level in order to have more daylight on the desk, and in order to allow as much view out as possible. The criterion for visual discomfort due to low illuminance on the desk (Lindelöf and Morel, 2005) (*VLDP*), is shown in figure 5 (left):

$$\begin{aligned} &if\ \ E_h < 10 :\ \ VDP = 1.0 \\ &if\ \ E_h > E_{opt} : VDP = (1 - VLDP_{\min}) \cdot (E_{opt} - E_h) / E_{opt} + VLDP_{\min} \\ &else\ \ VDP = VLDP_{\min} \end{aligned} \tag{3}$$

VDP is the general index of visual discomfort probability
$VLDP_{min}$ is the lowest achievable value of the discomfort index
E_h is the illuminance on the horizontal workplane, and
E_{opt} is the minimum illuminance level that will give the lowest value of *VLDP*

In the BSim simulation E_{opt} was set to 500 lux, while $VLDP_{min}$ was set to 0.2.

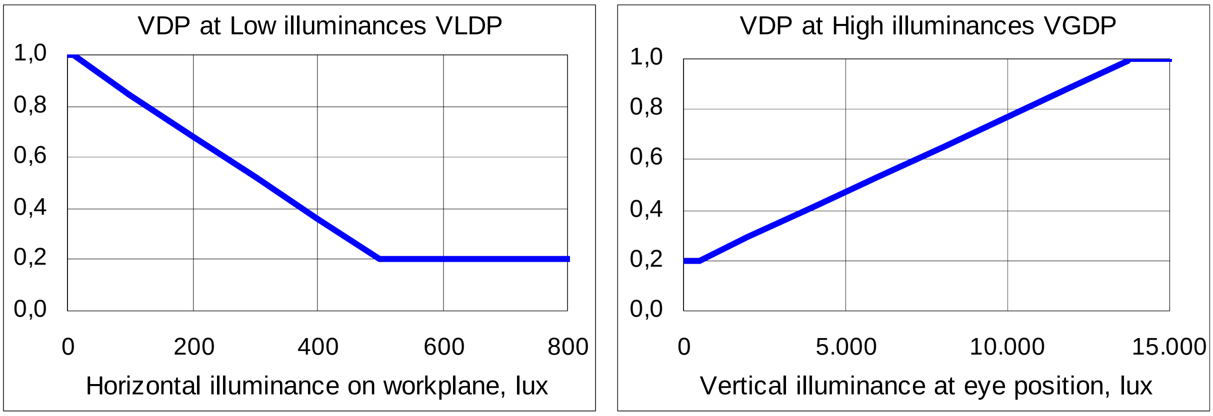


Figure 5. Left: The visual discomfort probability (VLDP) because of too little light on the desk. Right: Visual discomfort probability due to glare (VGDP) defined for the illuminance at the eye of an office worker.

SIMULATIONS

Simulations were made for the five different control strategies and for two climate conditions, Brussels and Rome, using Meteonorm weather data files (Meteonorm, 2006). In all simulations realistic operation conditions were assumed for lighting and ventilation. A daylight control system was simulated, taking into account the influence on the daylight level for each position of the blinds. The mechanical ventilation and cooling systems were set to keep the indoor temperature below 25°C during office hour, to the extend possible.

RESULTS

Visual discomfort probability

The simulation results showed significant differences in the VDP index for glare, figure 6.

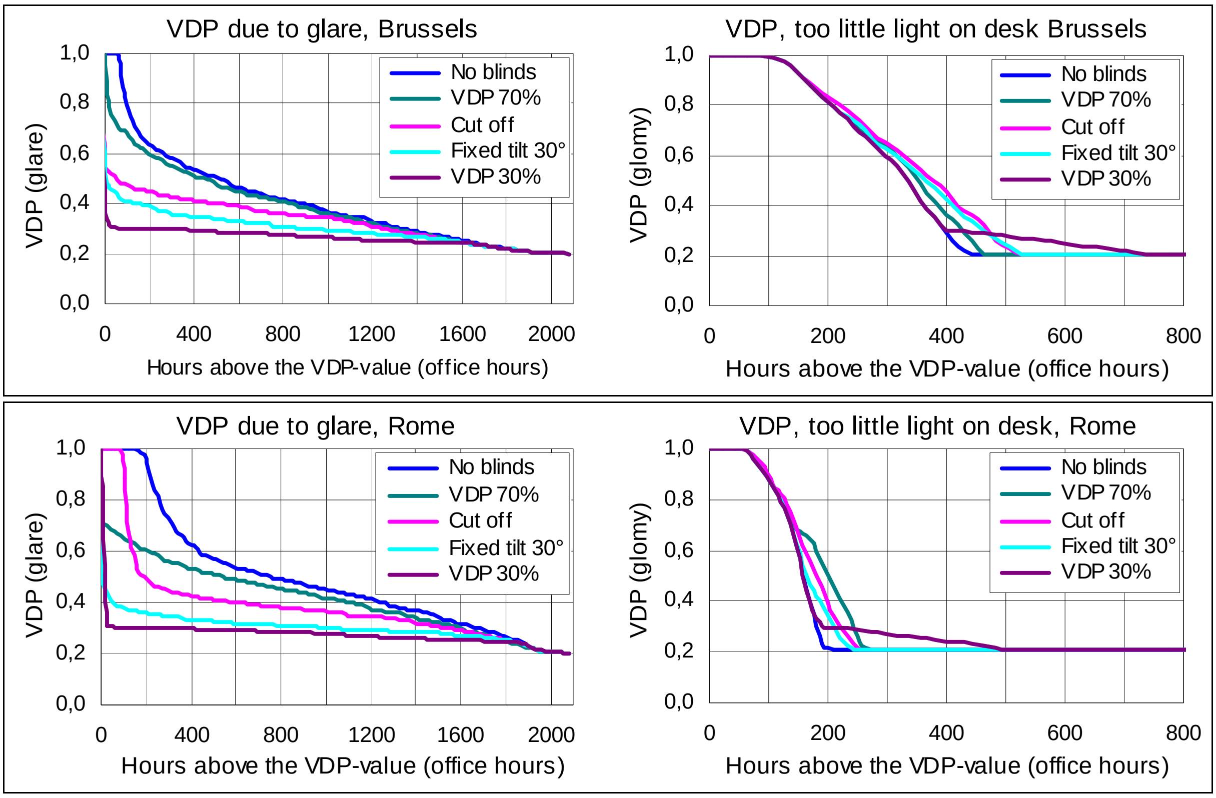


Figure 6. Visual discomfort probability due to glare(left) and because of too little daylight on the desk (right) for Brussels (top) and for Rome (bottom).

It turned out that the most advanced of the existing shading control systems, the cut-off strategy, is not capable of preventing glare, which means that glare is not just a question of direct sun, but it may also often occur because of high sky luminance. The new glare control strategy managed to keep the Visual Discomfort Probability below the chosen limit in almost all working hours both in the Brussels and in the Rome case. From the right graphs it can be seen that the VDP 30% had a small cost in available daylight on the desk, resulting in a higher number of hours where VLDP exceeded 0.2, than the other cases. The figures also show that a fixed slat angle strategy may be more favourable than the cut-off strategy both regarding visual discomfort due to glare and due to too little light on the desk.

Thermal discomfort

For each of the control strategies the cumulated frequencies of the operative temperature distribution within office hours was calculated by BSim as shown in figure 7. The results show that for the Brussels case there were no real problems with overheating, except for the case without the shading. For the Rome case there were a significant number of hours above comfort level with all control strategies. The worst case was the VDP 70%: Accepting a Visual Discomfort Probability (VDP) up to 70% almost doubled the number of office hours above 25°C compared to the case of VPD 30%. This was in spite the fact that energy analysis showed that the cooling energy at the same time increased by approximately 10% (see below). The figures also indicate that the cut-off strategy allowed too high solar loads during the summer (or at least on hot summer days), for instance when compared with the fixed 30° slat angle control.

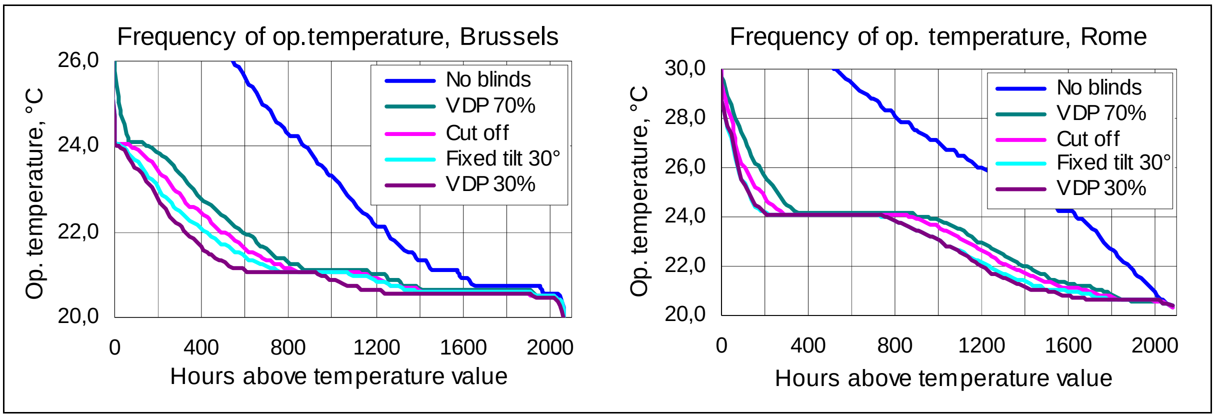
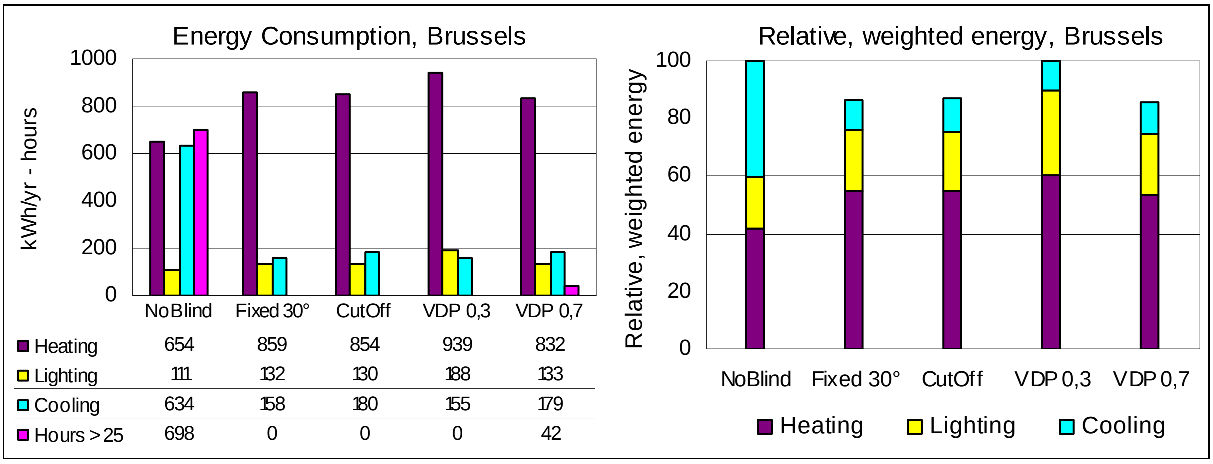


Figure 7. The graphs show the cumulated frequency of operative temperature with the different blind control strategies for Brussels and for Rome.

Energy consumption

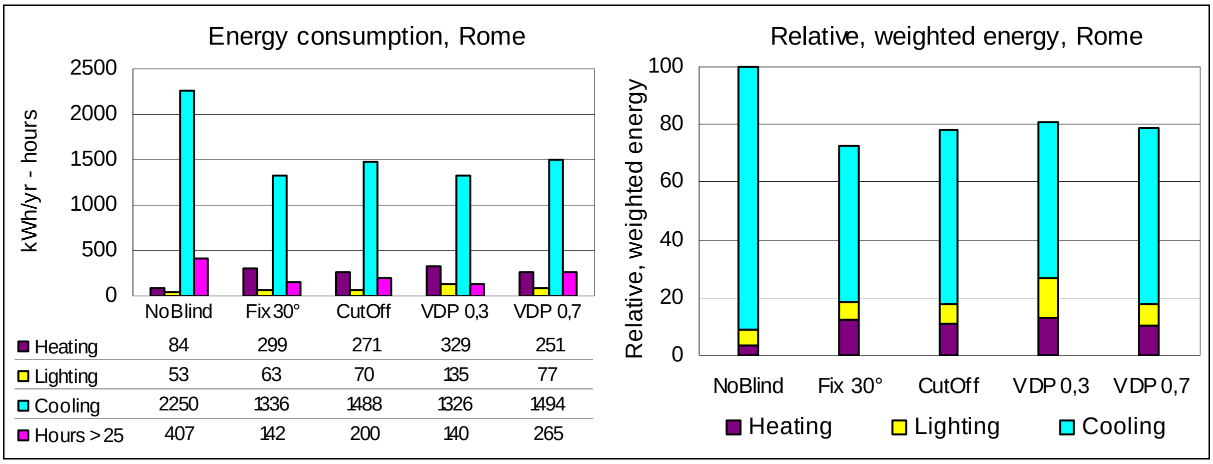
For each simulation case the complete yearly energy balances were calculated in BSim. From the energy balances comparisons were made of the energy consumption with the different solar shading control strategies, as shown in figure 8 and figure 9. The heating demand is the sum of the heat from the electric heater and the heating coil in the ventilation plant. In the comparison of the energy consumption for the different control strategies the absolute figures are given in kWh/year for the office as well as the relative, weighted consumptions, where electricity is multiplied with 2.5 compared to heating and cooling energy.



	NoBlind	Fixed 30°	CutOff	VDP 0,3	VDP 0,7
■ Heating	654	859	854	939	832
■ Lighting	111	132	130	188	133
■ Cooling	634	158	180	155	179
■ Hours > 25	698	0	0	0	42

Figure 8. Brussel: Energy for heating, cooling and lighting plus the total number of office hours where the operative temperature exceeded 25°C for the 5 control strategies, and relative, weighted energy consumption, where electricity is multiplied by 2.5 compared to heating and cooling energy.

First of all the results showed that an efficient shading device was needed both to maintain an acceptable indoor climate and to reduce energy consumption. The results showed that keeping the visual discomfort probability below 30% gave a somewhat higher energy for heating and for lighting compared to the other cases. For the Brussels case the difference was around 10% extra for heating and 40% extra for lighting. For the Rome case the difference was 10-30% extra for heating, while it was almost 100% extra for lighting. The energy for cooling and the number of hours above 25°C are somewhat smaller in the VDP 30% case due to lower solar loads in this case, see figure 9.



	NoBlind	Fix 30°	CutOff	VDP 0,3	VDP 0,7
■ Heating	84	299	271	329	251
■ Lighting	53	63	70	135	77
■ Cooling	2250	1336	1488	1326	1494
■ Hours > 25	407	142	200	140	265

Figure 9. Rome: Energy needed for heating, cooling and lighting plus the total number of office hours where the operative temperature exceeded 25 °C for the 5 control strategies, and relative, weighted energy consumption, where electricity is multiplied by 2,5 compared to heating and cooling energy.

DISCUSSION

As a mean to investigate the indoor climate and energy aspects of shading devices controlled in accordance with the users' visual needs, new models were implemented in the thermal simulation software package BSim. Solar shading control based on the visual comfort criterion as expressed by the Visual Discomfort Probability index significantly improved the visual comfort. For the blinds simulated it was possible to keep the VDP index below a chosen value, for instance VDP < 0.3, for almost all office hours. (By definition the VDP index can not be smaller than 0.20). However, while the illuminance level "on a vertical plane at eye position" relatively easy can be calculated, it is not easy to meausre in reality. Therefore it is important to notice that there is a strong correlation between illuminance at the eye position and the illuminace on the sidewall behind the user, looking in a direction parallel to the window, (Velds, 2000). In the simulations the illuminance values in the reference points were pre-calculated in the Radiance software. Simplified models for daylight reduction by using Venetian blinds (or other types of lamella based shading devices) has now been implemented in the BSim software so that the glare control can be simulated directly.

CONCLUSIONS

Users activate the shading device when they are visually annoyed or disturbed by high luminances in the field of view, rather than because of high solar loads or high indoor temperatures. The results showed that even the most advanced existing shading control system (cut-off strategy) do not meet the users' need for protection against glare. The described glare control strategy seems to describe a more realistic control of shading devices, and has a great potential for improvement of the visual comfort in office buildings. It should be noted however, that there may be a small cost in energy consumption, especially in cold climates.

ACKNOWLEDGEMENT

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