Tore Kolås

Performance of Daylight Redirecting Venetian Blinds for Sidelighted Spaces at High Latitudes

Performance analysed by forward ray tracing simulations with the software TracePro

Thesis for the degree of Philosophiae Doctor

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Norwegian University of Science and Technology
Faculty of Architecture and Fine Art
Department of Architectural Design, Form and Colour

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Norwegian University of Science and Technology

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Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) as part of the requirement for the degree of Philosophiae Doctor (PhD). The work presented here has been a part of the project *Smart Energy Efficient Buildings,* a strategic project at NTNU and SINTEF, and has been carried out at the Faculty of Architecture and Fine Art at NTNU.

Since my academic background prior to this project is from the field of physics, the switch to working with daylight in buildings has been a very interesting and rewarding challenge. The presented work is of a multidisciplinary character, including not only daylighting in architecture but also building physics, lighting engineering, optics and computer simulations. This is partly a reflection my experience with several of these fields during my prior work on various research projects at SINTEF, including projects related to the development of reflector materials and electric lighting systems.

My interest for daylighting goes back to the days of my graduate studies, but my real experience in this field started with a research project named *Hybrid Lighting in Buildings.* The main idea behind the hybrid lighting concepts explored in that project was to develop electric lighting solutions that also enhanced the utilisation of daylight through window openings. The hybrid lighting project was carried out in the years from 2000 to 2006 and was managed by the electric lighting company Luxo, in close collaboration with NTNU and SINTEF.

The work presented in this thesis started in the year 2004. During the following years I have kept my position as a researcher at SINTEF. The main positive effect from this is that the fundamental academic work has been a platform for several SINTEF projects of a more applied character. However, it has also been a bit frustrating at times, not having the opportunity to concentrate fully on one single project.

The completion of this thesis therefore marks the finish of a long journey. Hopefully, the reader will find the following pages of interest.

Acknowledgements

During the years that I have spent working on this project I have benefited from the help and guidance of many people. This thesis would not have been possible without their contribution.

First and foremost, I would like to express my gratitude to my supervisor, Professor Barbara Matusiak, for her support and flexible guidance during this project; from start to finish. Her knowledge and experience in the field of daylighting in architecture has been of invaluable importance for my work.

I also acknowledge my co-supervisor, Professor Ola Hunderi, for the constructive discussions and helpful advice he has provided throughout the project.

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The contribution from Dr. Matthias Haase was also of great importance. In particular, I would like to emphasise that he carried out all the presented Radiance simulations, which were essential for validation purposes.

Finally, I have had the privilege to work with many people representing various departments and disciplines. The list is too long to name them all, but I would like to express my sincere appreciation to all my present and former colleagues at NTNU and SINTEF who have contributed to the fulfilment of this thesis.

Abstract

The main topic of this thesis is daylight in buildings. More specifically, the thesis presents studies on the performance characteristics of venetian blinds used on the interior side of vertical windows. A particular emphasis is put on the daylighting properties of different blind types, and the performance of daylight redirecting blinds is compared to the performance of traditional white blinds.

Three factors are highly important for daylight in buildings: the daylight source, the optical properties of the fenestration or daylighting system, and the characteristics of the architectural space that receives the daylight.

Earlier works on daylighting systems in buildings have often documented the daylight levels and the daylight distribution within the space. With that approach it can be hard to pinpoint exactly why one daylighting system performs differently from another.

For the work presented here it has been a goal to focus on the properties of the fenestration system itself, while operating under various daylight conditions that are relevant for high latitudes. Some assumptions have been made regarding the architectural space (sidelighted with an elevated daylight opening), but apart from this it has been sought to describe the system performance more or less independently from the architectural space.

This approach can be compared to the approach that has been used in the field of electric lighting. There, luminaries are typically specified by performance characteristics that are not depending on the space in which they are to be applied. For electric luminaries, photometric properties such as luminous flux, light distribution and light output ratio are commonly used to describe the performance of the luminaire, and these values are independent of the space where the luminaire is to be used.

In other words, in this thesis, the venetian blind system is treated more or less as a "daylight luminaire".

The main tool applied to analyse the photometric properties of the "daylight luminaire" is Monte Carlo forward ray tracing. The software TracePro is used extensively for this purpose. This software tool is tailor-made for analysing optical systems (including luminaries).

Unfortunately, daylight sources are not available in TracePro. For this reason, a substantial effort was made in order to generate TracePro light sources that represent the light from ground, sky and sun. However, once these sources were established and validated, many positive features of the program could be utilised with good effect in order to quantify a variety of different photometric

characteristics (e.g. transmittance, light distribution and luminance) of venetian blind systems.

In order to analyse these characteristics in a systematic manner the *fundamental* geometrical properties of venetian blinds need to be understood and these properties have therefore been derived and described.

A new evaluation method for daylight redirection systems is presented in this thesis. This method is based on quantification of performance metrics already applied for such systems combined with new performance indicators suggested on the basis of literature findings as well as own studies of venetian blind performance.

The main goal of the new method is to provide a tool that can be used to indicate performance of a particular system with respect to 8 different important criteria that are determined by the properties of the daylighting system: (1) supply of daylight, (2) room darkening, (3) light distribution, (4) glare protection, (5) outward view, (6) privacy protection, (7) solar heat supply, and (8) overheating protection.

Star diagrams are used to provide a graphical illustration of the performance of the systems, where each of the 8 star points represents one of the 8 performance criteria used to evaluate the system.

The new evaluation method has been applied in order to compare the performance of traditional white blinds with that of daylight redirecting blinds. The results show that, when both blinds are operated in the semi-closed position, the performance is roughly the same for all of the performance criteria considered. However, when both blind types are operated in the open blind position, the daylight redirecting blind can perform better with respect to daylight supply and light distribution. The results presented in this thesis also show that these benefits can be obtained without worsening the performance with respect to the other criteria.

The performance of blinds has been studied for daylight conditions that are representative for high latitudes. It has sometimes been argued that, due to the typical low sun conditions, especially during the winter months, daylight redirecting blinds are less suitable at high latitudes. However, results presented in this thesis show that daylight redirecting blinds can function very well under most sun conditions that are typical for high latitudes, provided that the spacing to width ratio is carefully selected.

Contents

Symbols

Uppercase Latin symbols

A	surface area [m^2]
D	distance between cuts in laser cut panels [m]
E	illuminance [lux]
I	luminous intensity [cd]
L	luminance [cd/m^2]
L_a	luminance of a sky element [cd/m^2]
L_z	zenith luminance [cd/m^2]
O	overlap between adjacent blind slats
S	spacing between slats in louver/blind systems [m], daylight scene
T	temperature [K]
U	uniformity of illuminance levels, heat transfer rate (U-value)
V_λ	spectral eye sensitivity curve
W	width of fenestration system component (blind, panel, etc.) [m]
Z	angle between a sky element and zenith

Lowercase Latin symbols

a	absorptance on blind slats
d	depth [m]
f	free view fraction
fd	fraction of deflected light (in laser cut panel)
fu	fraction of light transmitted without deflection (in laser cut panel)
g	total solar energy transmittance (g-value)
h	height [m]
n	index of refraction, number of rays
q	heat transfer factor
r	radius [m], reflective blind
t	thickness [m]
w	width [m], white blind

Subscripts

a	sky element
avg	average
c	curvature
con	continuous
const	constant
d	diffuse reflectance
diff	diffuse, diffuser
dir	direct, directions
ext	exterior (side)
FR	first reflected
fs	fenestration system
glob	global, total
gr	ground reflected
hor	horizontal
i	internal, incident
int	interior (side)
IRC	internally reflected component
max	maximum
per	perimeter zone
perp	perpendicular
RAD	Radiance
s	specular reflectance, sun, sky
sel	selected
sol	solar, sun
t	transmitted
tot	total
TP	TracePro
up	upward
ver	vertical
vis	visual, visible
win	window
z	zenith

Greek symbols

α	azimuth angle [deg], absorptance on blind slats
β	slat tilt angle
γ	elevation angle above the horizon [deg]
Δ	difference
ε	thermal emissivity
ρ	reflectance
τ	transmittance
Φ	luminous flux [lm]
χ	angle between the sky element and the sun [deg]
ω	wavelength [μm]
θ	angle of incidence [deg]
Ω	soild angle [rad]

Abbreviations

CB	closed blinds
CIE	Commission Internationale de l'Eclairage
DA	daylight autonomy
DC	direct component
DGI	daylight glare index
G	glare index
HOE	holographic optical element
LCP	laser cut panel (Edmonds panel)
LED	light emitting diode
LIF	luminous intensity fraction
LOR	light output ratio
MIT	Massachusetts Institute of Technology
N.A.	not applicable
NB	no blinds
NTNU	Norwegian University of Science and Technology
P	position index
PV	photovoltaic
PVC	polyvinyl chloride (plastic)
SBi	Danish Building Research Institute
SINTEF	The Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology
TP	TracePro
UDI	useful daylight illuminances
VDU	visual display unit
VTP	view through potential

1 Introduction

Daylight is a gift of nature.

Ralph Galbraith Hopkinson

1.1 Background

The need for lighting in modern buildings is met by two very different approaches; artificial lighting and daylighting. The relative importance of these two approaches has varied significantly over the years. At the beginning of the 20th century, the use of daylight was still the most important approach used to light the interiors of buildings. In the following years technological advances in electrical lighting made it possible to supply a building with artificial light 24 hours a day. This made electrical lighting the main contributor to meet the lighting needs in buildings and the importance of daylighting was significantly reduced. Today, the trend has again shifted, as the positive aspects of daylight are more highly appreciated. This includes the potential for significant electrical energy savings, as well as the positive effect daylight has on the health and well-being of building occupants.

The most common daylight opening in a building is the vertical window and the benefits of daylight through windows are well documented. The two main attractions of windows are that they provide a view out for the building occupant and that they allow daylight to penetrate into the building interiors. In addition, opening the window can further increase the contact with the outside and provide fresh air to the occupant. On the negative side, windows can often be a source of visual and thermal discomfort for the occupants, as well as lack of privacy. In addition, the light distribution within the interiors resulting from daylight through windows is often far from ideal. As a result of unsatisfactory daylight distribution, sidelighted spaces can often be perceived as gloomy.

Various solar shading and daylight redirection systems are used to limit the negative attributes of the window opening and to improve the daylight quality within the interiors. This includes both simple solutions such as window curtains as well as sophisticated daylight redirection systems such as for example prismatic panels or the sun-directing glass.

The venetian blind has, for a long period of time, kept its position as one of the most preferred shading devices, particularly in commercial buildings. The traditional venetian blind can therefore be considered as a classical shading device.

In addition to solar shading, the venetian blind can be used to protect against glare, to reduce the interior lighting levels, and also for privacy protection. Another positive attribute of venetian blinds is that, in many cases, depending on the slat tilt angle, at least a limited view out of the window between the blind slats is maintained even at times when the blinds are lowered.

Today, daylight redirecting venetian blinds are also sometimes used, mostly for elevated window areas located above the eye height of building occupants. Daylight redirecting venetian blinds typically have a specularly reflective upper surface and a curvature that is upside down compared to the traditional venetian blind. Daylight redirecting venetian blinds are designed both to admit more daylight into the building interiors as well as to redirect sunlight via the ceiling towards the deeper building interiors where it is presumably more needed.

1.2 Problem

Despite the alleged superior properties of daylight redirecting blinds, such systems are not very frequently used, especially not at high latitudes. According to the distributors of venetian blinds the demand for traditional blinds, preferably of a light colour, is many times higher than that for daylight redirecting blinds.

The reasons for this lack of demand could be many. One obvious reason to consider is that the cost of daylight redirecting blinds is generally somewhat higher than that of traditional venetian blinds. Today, manually operated blinds are often chosen, even though several studies have shown that the energy saving potential increases with automated blinds. For daylight redirecting blinds it is of particular high importance to adjust the blind tilt according to the position of the sun, and it can be argued that daylight redirecting blinds will lose most of their superiority when they are operated manually. Again, the high costs associated with automated solutions could, at least partly, explain the low demand for daylight redirecting blinds. Also, in order to save electric lighting energy by utilisation of daylight the electric lighting installation should be provided with daylight linked dimming, which has not been customary until very recently.

Another reason could be that the true advantages of daylight redirecting blinds are not understood by the people that take part in decisions related to the choice of shading systems or daylight redirection systems in a building; architects, consulting engineers, building owners, and even researchers. One example of this is that daylight redirecting blinds are often said to be ineffective at high latitudes, due to the low sun conditions that are typical at high latitudes, especially during the winter season. Is this statement really true, and if so, is this only a result of the blinds not being designed for operation at high latitudes?

A final reason could be that the properties of the daylight redirecting blinds are actually not really significantly better than that of the traditional venetian blinds. Is it possible that the low demand for daylight redirecting blinds simply reflects that the properties of the daylight redirecting blinds are not superior to the commonly used white blinds?

A large number of studies of venetian blinds have been carried out in the past. This includes studies related to user behaviour, to control systems for blind operation as well as to the potential for energy savings. Also, some studies of the light and heat transmittance through venetian blind systems have been conducted. However, so far, no comprehensive and systematic study has been carried out that compares the performance of traditional white blinds with that of daylight redirecting venetian blinds.

It is argued here that, in order to take full advantage of the potential benefits provided by daylight redirecting venetian blinds, it is imperative to obtain a fundamental understanding of the performance of such systems, including not only the benefits but also the potential shortcomings.

1.3 Main objectives

The main objective of this work is to investigate and document the performance characteristics of venetian blinds in a systematic manner. The main focus is on venetian blinds located in elevated window openings (above eye height) in sidelighted spaces at high latitudes. Since no comprehensive methods for performance evaluation are available, a major objective of this work is to propose such an evaluation method.

As discussed below (in section 1.6), forward ray tracing simulations is the most important tool utilised here in order to quantify the performance of venetian blind systems. Ray tracing simulations are carried out both for a traditional white venetian blind as well as for a daylight redirecting venetian blind with a specularly reflective upper surface. Following from this, the main objectives can be summarised:

- To provide new knowledge with respect to the performance of venetian blinds in general and daylight redirecting venetian blinds in particular.

- To propose a new method for evaluation of venetian blinds located in elevated window openings in sidelighted spaces.

- To compare the performance of a traditional white venetian blind with that of a daylight redirecting (reflective) blind; both operating at high latitudes.

- To explore the possibilities in applying forward ray tracing to study various attributes that are relevant for the performance of venetian blinds.

1.4 Hypothesis

The main hypothesis is that daylight redirecting blinds with a specular upper slat surface have the potential to perform significantly better than the traditional white blind in providing useable daylight to the interiors of a sidelighted space.

Furthermore, the relatively low sun elevations that are typical at high latitudes provide good conditions for efficient redirection of sunlight towards the deeper interiors, provided that the daylight redirecting blind is designed to operate at high latitudes.

1.5 Approach

The assessment of daylight in buildings is a multifaceted problem. The final result is influenced not only by the characteristics of the daylighting system, but also by the given daylight conditions as well as the properties of the space in which the daylighting system is applied.

Most of the commonly used methods to evaluate daylight in buildings actually describe the *combined* performance of the daylighting or shading system and the space in which the system is applied. Furthermore, this *combined* performance is described either for a particular daylight scene (typically overcast sky), or as a time-integrated performance over a year, for a selected geographical location.

It is argued here that, by applying such methods, the actual performance of the daylighting or shading system itself is sometimes lost in the complexity of the other factors.

For this reason a different approach will be used here, where the focus is on performance characteristics that convey information about the properties of the daylighting system itself, and not on the system in combination with a particular space. Naturally, some assumptions with respect to the space must be made, but the aim is to focus on performance characteristics that are more or less independent on the characteristics of the space.

The overall approach followed here is to concentrate on the system properties that are intrinsic for the venetian blind solution to be evaluated. The general idea is that such an approach will make it easier to pinpoint the performance characteristics that are originating from the system itself, without being diverted by the properties and peculiarities of the space in which the system is used. This approach can be compared to the approach that has been used in the field of electric lighting. There, luminaries are typically specified with performance characteristics that are not depending on the space in which they are to be applied. For electric luminaries, values such as the luminous flux, light distribution and the light output ratio are commonly used to describe the performance of the luminaire, and these values are completely independent of the space where the luminaire is to be used.

As described below, the forward ray tracing software TracePro is extensively used in the effort to meet the main objectives. It is considered to be of significance that this software is generally very suitable for studying the optical performance of a system. TracePro includes several analysis tools that are helpful for extracting information of the optical characteristics of a system, and as shown in the following, these tools can also be utilised in characterising the performance of venetian blinds.

1.6 Scientific method

Forward ray tracing simulations is the most important scientific technique utilised to reach the project objectives. More specifically, the software TracePro from Lambda Research Corporation is applied.

TracePro is designed to carry out forward ray tracing simulations based on the so-called Monte Carlo method. TracePro has been extensively used for optical analysis and design, within several fields, including that of illumination engineering. However, at least until now, TracePro has not been tailor-made for the field of daylighting.

Since TracePro has not been designed primarily for daylighting applications, new models of light sources, representing daylight through a window opening are needed in order to use TracePro to analyse the performance of venetian blinds under various sky conditions. The daylight sources that have been developed for this purpose have been validated through analytical work as well as through comparison with simulation results obtained from the daylighting software Radiance.

1.7 Scope and limitations

As the title indicates, venetian blinds are the main focus of the work presented here. Venetian blinds refer to slat type daylight redirection or shading system with equally spaced horizontal slats. Although venetian blinds are the main focus of attention, many of the findings are of a more general nature, and are of relevance for other types of daylighting and shading systems.

The new evaluation method presented in the following is intended primarily for daylight redirection systems with horizontal slats located in elevated positions in the window facade of a sidelighted space – above the eye height of a building occupant. However, once again, many of the findings are of relevance also for other systems and applications, for example for traditional venetian blinds located in view windows positioned below eye height.

The main emphasis is on office spaces, and the reason for this is two-fold. Firstly, office spaces are well documented in the literature of daylighting, and secondly, both venetian blinds in general and daylight redirecting blinds in particular are frequently used in office buildings. Nevertheless, again the findings presented in the following are in general relevant for many types of sidelighted spaces.

In practice, the slats of most venetian blinds are slightly curved and the slats have a given physical thickness. In the work presented here, the focus is on blinds with flat slats, and the effect of slat thickness has not been studied. Still, in section 15.7 it is argued that most of the results presented here will hold also for venetian blinds with a typical slat curvature and slat thickness.

In general, shading systems can be located either on the exterior side of the glazing, between window panes, or on the interior side of the glazing. The work presented here only considers venetian blinds located on the interior side of a double glazing unit. The precise location of the blind is known to have a strong effect on the solar heat gains through the fenestration system. However, for most of the other properties discussed, the location of the venetian blind system with respect to the window panes plays a lesser role. Most of the conclusions presented are therefore considered highly relevant for venetian blinds located between window panes, and some of the findings are also applicable for exterior blinds.

As the title suggests, the scope of the work presented here is focused on systems operating at high latitudes. High latitudes here refers to the geographical regions with latitudes from 55º or higher. The emphasis on high latitudes has mainly put restrictions on the solar elevation angles that have been investigated. In the work presented here, as a result of this limitation, only solar elevation angles up to 50º are considered. This makes the simulation results less relevant for low latitudes but the findings are still of some relevance to mid-latitudes (35º to 55º), especially for predicting performance during the winter season. It should also be noted that the new evaluation method presented is not at all restricted to high latitudes, and could readily be applied to extract information about the performance of a system operating at any geographical location.

Finally, as the subtitle indicates, the work presented here is based on the results from theoretical considerations and computer simulations carried out with the forward ray tracing software TracePro. No physical experiments have been carried out to assess performance or to validate the computer simulations. However, all of the performance indicators presented in the new evaluation method are measurable quantities. Therefore, it is fully possible to carry out a performance assessment of venetian blinds according to the proposed method based on physical measurements alone, without the aid of computer simulations.

1.8 Contents

In order to obtain a fundamental understanding of venetian blinds it is first necessary to understand how building occupants regard the positive and negative impacts of both windows and daylighting in general as well as venetian blinds in particular. The state of the art regarding daylight in buildings is the subject of chapter 2, while daylight redirection and shading systems are discussed in chapter 3.

The fundamental properties of venetian blinds are the subject of chapter 4. The results presented in this chapter depend mainly on geometrical considerations. This chapter also includes a discussion about the geometrical parameters that are needed to define blinds with horizontal slats.

Daylight simulations with TracePro are discussed in chapter 5. As mentioned above, TracePro has not been designed primarily for daylighting applications. The main aim of this chapter is to document the new daylight sources that have been developed for TracePro, as well as the mathematical descriptions of the sky and sun, on which the new daylight sources are based.

In chapter 6, a sidelighted reference space is introduced. The new daylight sources developed for TracePro are validated by comparing the resulting floor illuminances obtained from the TracePro simulations with results obtained from the software Radiance, which has commonly been applied in daylighting simulations. In chapter 7 the reference space is used in order to study the floor and ceiling illuminances obtained with various different venetian blind solutions and for different daylight conditions.

Results from TracePro simulations are also presented in chapters 8 to 11. However, the results presented here are of a more fundamental character in that they are not obtained for a particular space, but rather are aimed at conveying information about the properties of the venetian blind systems themselves; light transmittance properties (chapter 8), the angular distribution of the transmitted light (chapter 9), the average window luminance (chapter 10), and the solar energy transmittance (chapter 11).

Based on the findings presented in earlier chapters, a new evaluation method for daylight redirection systems is presented in chapter 12. Following from this, in chapter 13, the new method is applied to study and compare the performance of a traditional white venetian blind with that of a daylight redirecting (reflective) blind. In order to make the performance characteristics of a particular system more accessible, star diagrams are introduced in chapter 14, and examples of such diagrams for a white blind and a reflective blind are provided. Finally, the two last chapters (chapter 15 and 16) concludes the work with a discussion about the new evaluation method, as well as of the findings related to the performance of the daylight redirecting blind operating at high latitudes.

2 Daylight in buildings

Architecture is the masterly, correct, and magnificent play of masses brought together in light.

Le Corbusier

2.1 Introduction

In this chapter a literature and state of the art review of daylighting is given. The main aim of this chapter is to provide a platform for the further chapters. This includes in particular an understanding of how building occupants regard the positive and negative impacts of both venetian blinds in particular, as well as windows and daylighting in general. Included here is also a discussion of occupant needs and preferences with respect to windows and daylight, current lighting recommendations and methods used to assess daylight in buildings, as well as user patterns for manual operation of venetian blinds.

In addition, economic considerations related to lighting are included, since such considerations are of importance with respect to the practical feasibility of applying daylighting solutions in buildings.

2.2 Occupant needs and preferences

For building occupants, windows provide a visual opening towards the exterior surroundings. Windows are known to influence the comfort of building occupants both positively and negatively, determined by factors such as the need for outdoor view, privacy and sunlight. Windows also influence the building energy consumption, through mechanisms such as solar energy gains and heat losses.

A thorough understanding of the building occupant's needs and preferences with respect to windows and daylight is the foundation for all good daylighting design and evaluation of performance. This includes factors such as necessary lighting levels, the importance of sunlight and view, preferred window sizes as well as preferences with respect to particular technological solutions. Several studies have been carried out with the aim to improve this understanding and in this section a brief review of the findings is given.

2.2.1 Main attributes of windows

Numerous studies in office buildings have concluded that people value daylight and prefer to have their workplace located near windows (Collins 1975) (Heerwagen and Orians 1986) (Christoffersen, Petersen et al. 1999). The literature indicates that the possibility for contact with the natural surroundings is the single most important attribute associated with windows. This includes both the possibility for outward viewing, to have something interesting to look at, and to be able to keep track of time and weather (Ne'eman and Hopkinson 1970) (Ludlow 1976).

An interesting experimental study was carried out by Young and Berry (1979). They investigated user preferences in offices equipped with either an ordinary window or an artificial window. The ordinary window supplied both a view towards the exterior surroundings as well as daylight to the interiors, while the artificial window supplied a dynamic view over a natural landscape but no daylight. The results showed that there was a minimal difference in preferences for the two window types. According to Boyce and Hunter et al. (2003), this study indicates that the possibility for a view is the one attribute that dominates our preference for windows.

The conclusion that the possibility for a view dominates our preference for windows is also supported by several studies carried out in England (Ne'eman 1974; Ne'eman, Craddock et al. 1976). Here, the preferences between sun shining into the building interiors and a good view out of a window but no interior sunlight was investigated for four different building types; residential houses, schools, offices and hospitals. In all four cases the results indicated a preference for a desired view with no interior sunlight over interior sunlight combined with an undesirable view. For the office buildings, 61% of the respondents preferred the desired view while 36% preferred interior sunlight. Ne'eman remarks that the research was conducted in England, where the amount of sunlight is limited compared to other regions, and that the findings may not be representative for other locations.

The importance of the view is also supported by the results from a study carried out on office workers in Denmark (Christoffersen, Petersen et al. 1999). Here the three properties of windows with the largest positive significance were found to be: (i) to be able to see out, (ii) to be able to keep track of the weather outside, and (iii) to be able to open the window to increase ventilation. A main conclusion from this study was that people preferred to have their workplace near a window, even if they were bothered by glare and reflections in computer screens. More than 70% of the workers had their computer located next to a window.

2.2.2 Outward viewing preferences

The literature indicates a preference for natural views over built or urban views. This has been found in numerous studies e.g. by Marcus (1967) and Kaplan (1989). Studies by Ne'eman (1974) (1976) showed a preference for natural sceneries, but also activity, that something happens, was found to be desired.

The study by Christoffersen (1999) also showed that the office workers preferred a view over natural landscapes; trees and grass or sky. A preference for views containing a certain variety as well as dept or panorama was also reported. This can be fulfilled when the office worker is located high above the ground level. The study showed a great variation in the satisfaction of the view as a function of floor level, with higher satisfaction at higher floors. Especially pronounced was the difference in satisfaction between the view from the ground floor and that from the first floor. With respect to direct sunlight, the study showed a desire for direct sunlight at one or more seasons. The winter was found to be the season when direct sunlight in the office was most appreciated. However, an important prerequisite for the appreciation of sunlight was the possibility of controlling the sunlight by means of sun shading.

2.2.3 The value of a view

Is it possible to attain an economic value to our desire for windows and a view? This was the question that Kim and Wineman tried to answer in a study carried out in the USA (Kim and Wineman 2005). The researchers used an empirical approach, analysing data on building property values and conducting surveys in hotels, residential spaces and office buildings to measure whether spaces in buildings with better views generated higher retail income. The study also sought to empirically quantify the psychological value of views and windows measured by people’s seat selection patterns and preference to situate themselves near favourable views and windows. The results from this study showed that views and windows have both psychological and economic value, and that it is possible to quantify the economic value empirically.

2.2.4 Preference for daylight

People tend to value daylight higher than light from electric sources. According to Boyce (2003), the desire for daylight can be shown by evidence from four sources: from research, from behaviour, from advertising, and from finance.

The research literature shows a consistent strong preference for daylight over electric lighting. The preference for daylight is confirmed by surveys carried out in Great Britain (Markus 1967), in the USA (Heerwagen and Heerwagen 1986), in Canada (Veitch 1993) and in New Zealand (Cuttle 2002). Several reasons for the daylight preference are given, including daylights variation in intensity, colour and direction, as well as daylights ability to create a pleasant atmosphere in the interiors. Table 2-1 summarises the results from the study by Heerwagen (1986).

Table 2-1 Percentage of occupants preferring daylight or electric lighting. From Heerwagen and Heerwagen (1986).

Factor	Daylight better [%]	Electric lighting better [%]	No difference [%]	No opinion [%]
For psychological comfort	88	3	3	6
For office appearance and pleasantness	79	0	18	3
For general health	73	3	15	8
For visual health	73	9	9	9
For colour appearance of people and furnishing	70	9	9	12
For work performance	49	21	27	3
For jobs requiring fine observation	46	30	18	6

As noted by Boyce (2003) the conclusion that daylight is desired is also supported by the observation that employees of higher status in an organisation are commonly given offices closer to windows or with more windows. Also, in the advertising of light sources there is often the claim that an electric light source provides light similar to daylight, implying that daylight is what people desire. Finally, Boyce also notes that the rent charged for daylit offices is higher than that for non-daylit office spaces.

The preference for daylight has been associated with the popular belief that daylight supports better health. For older electric lighting installations this belief can be easily supported. For example, fluorescent lamps with magnetic ballasts produce light that flickers with a frequency of 50 Hz (in Europe). This flickering light has been reported to cause headaches for some people. However, modern fluorescent lamps running on high-frequency electronic ballasts have eliminated this shortcoming of the electric lighting.

Are there perhaps other shortcomings of electric lighting that can support the belief that daylight provides better health than electric lighting? Until recently, science could not provide adequate explanations to support the strong preference for daylight. However, this was radically changed as new light sensitive receptors in the eye were discovered. This is the subject discussed in the next section (2.2.5).

2.2.5 Lighting and health

The visual effects of light on humans have been studied for several hundred years. The two visual photoreceptors in the human retina are named rods and cones, and they were first observed, by microscopy, as early as 1722 by the Dutchman Anthony van Leeuwenhoek. Their functional role as light sensitive photoreceptors was identified in 1834 by Gottfried Reinhold Treviranus from Germany. The two visual photoreceptors enable humans too see. The rods serve vision at low light levels (scotopic vision) and the cones serve high resolution colour vision at high light levels (photopic vision). The peak sensitivity for both receptors is to be found for green light with wavelengths of 507 nm and 555 nm respectively, as illustrated in Figure 2-1. The spectral eye sensitivity curve (V_λ) for the cone system (photopic vision) is the basis for lighting units such as lumen, lux and candela.

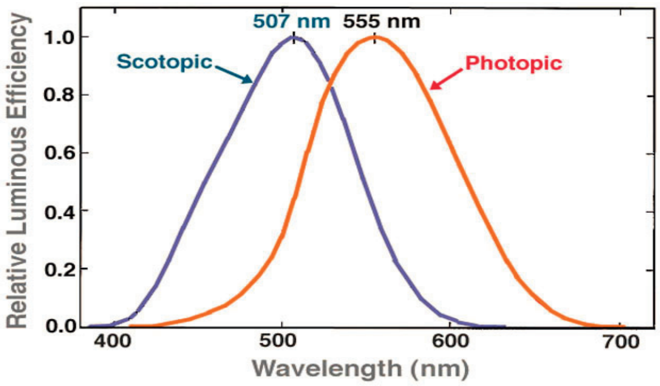


Figure 2-1 The scotopic and photopic curves of relative spectral luminous efficiency as specified by the CIE. Normalised values. Illustration reprinted from www.webvision.umh.es.

For more than 150 years, scientists considered cones and rods to be the only photoreceptor cells in the human eye. However, as recent as in 2001, two research groups independently reported results that indicated a new photoreceptor in the eye that could suppress melatonin levels in humans (Brainard, Hanifin et al. 2001) (Thapan, Arendt et al. 2001). The new receptor showed peak sensitivity for blue light, as peak wavelengths of 464 nm and 459 nm were reported. See Figure 2-2.

Following from this discovery it was evident that the light that enters through the human eye, apart from the visual effect, also has an important biological effect. It has been shown that light controls the human biological clock and regulates the secretion of several important hormones, and that these processes are important for human health.

Also, the practical implications of these findings for work place lighting has been discussed (Rea, Figueiro et al. 2002) (Aries 2005) (van Bommel 2006). The main conclusions from these discussions are that there is a need for a new lighting practice, including new recommendations for office lighting that can meet not only the visual needs, but also the needs for healthy lighting.

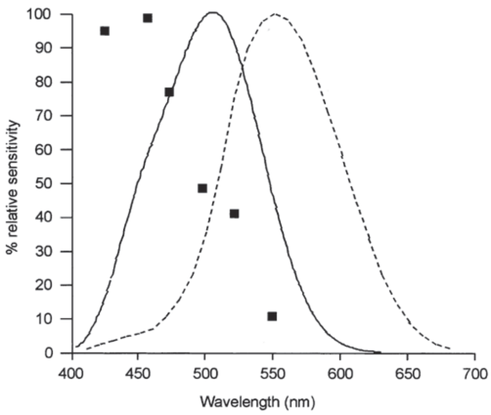


Figure 2-2 Action spectrum for melatonin suppression (dots) compared to the scotopic sensitivity curve (continuous line) and the photopic sensitivity curve (dashed line). Illustration from Thapan et al. (2001).

2.3 Lighting recommendations

2.3.1 Illuminance needs and recommendations

The preferred illuminance levels in offices vary strongly between individuals. The current lighting recommendations also reflect the need for energy conservation, and this leads to illuminance levels that are lower than what many office workers would desire. Current lighting recommendations are set to meet the visual needs of the office worker, and pay little attention to biological considerations. However, this could change in the near future, as the concept of healthy lighting is receiving increasing attention.

The requirement for task illuminance for offices varies between 200 lux and 750 lux according to the type of work (CEN 2003). For typical work places with computer workstations the requirement is 500 lux. Nevertheless, as noted by Aries (2005), most office workers prefer higher levels, typically above 800 lux.

The differences between the visual and the health related needs for lighting are discussed by Aries (2005), van Bommel (2006) and Andersen (2012). One important difference, as noted by van Bommel, is that the non-visual biological effect of light is not directly governed by the illuminance on the working plane, but by the light entering the eye. Therefore, for healthy lighting installations, it is no longer sufficient to specify only the illuminance on the working plane. Following from this observation, the focus on vertical illuminance levels in the offices environment has increased.

The newest European lighting standard (CEN 2011) provides recommendations for vertical illuminance in offices. The minimum levels for mean "cylindrical illuminance" and wall illuminance is set to 50 lux. However, the literature indicates that 1000-1500 lux might be required to meet biological needs. These high levels are not demanded all day and a dynamic lighting scheme should therefore be considered. Also, the light levels needed for biological stimulation depend on the spectral distribution of the light, and for blue light lower levels would be needed, as can be derived from Figure 2-2. It is clear that more research related to the biological lighting needs will be needed as a foundation for future recommendations aimed at assuring healthy lighting.

2.3.2 Guidelines for visual comfort

As will be discussed later (section 2.4.2), the assessment of glare from daylighting is a complex task. Even with all the work that has been carried out on glare assessment, it can be argued that the office environment is too complicated in order to predict the discomforts of glare. In fact, Osterhaus goes as far as to conclude that available assessment and prediction methods are of limited use in daylight office environments (Osterhaus 2005).

For this reason it can be argued that practical guidelines for visual comfort are of great importance. Luminance ratios within the field of view have often been used for this purpose. For visual comfort to be achieved the luminance ratios should not exceed certain limits. Typical recommendations assume a 1:3 ratio between the visual task and its immediate surroundings, a 1:10 ratio between the visual task and other near surfaces in the visual field, and a ratio of 1:20 for the more distant surfaces in the visual field. A 1:40 ratio between the task and any surface in the field of view is generally seen as the maximum permissible (Osterhaus 2009). If we assume that the visual task is a computer screen with a luminance of 150 cd/m^2, these recommendations limit the luminance in the field of view to a maximum value of 6000 cd/m^2.

The window luminance is a dominant factor for discomfort glare calculations for daylit spaces (CIE 1983). As commented by Wienold and Christoffersen (2006), in many regulations, especially in Europe, the average window luminance is used as a measure for glare and is restricted to a certain value. Some studies have shown that a window luminance of about 2500 cd/m^2 is often perceived as acceptable, whereas higher luminances might be perceived as discomforting (Fisekis 2003). Other studies indicate that higher average window luminances might also be acceptable and suggests upper limits between 4000 cd/m^2 and 6000 cd/m^2 (Platzer 2003).

2.4 Performance metrics for daylight in buildings

Several different methods have been proposed and used in order to quantify the daylight performance of a building. The performance with respect to providing sufficient daylight for carrying out visual tasks is important. This has led to several *illuminance-based* performance metrics, as will be discussed in section 2.4.1.

Furthermore, the ability to control glare is regarded as a major challenge for utilising daylight in buildings. Several different assessment methods have been proposed and used in order to quantify glare, as discussed in section 2.4.2.

Other factors that are important for daylight quality in buildings are the distribution of the light as well as the directivity. These factors have also resulted in performance metrics, as discussed by Cantin and Dubois (2011), but will not be elaborated on here.

In a later section (3.9) the performance metrics used for assessing daylighting systems is discussed.

2.4.1 Illuminance performance

The *daylight factor* is the most commonly used measure for the daylight performance of a building. The daylight factor has been used for several decades, and legislation to assure adequate daylight in buildings often refers to the daylight factor. In fact, the daylight factor has been so dominant that, according to Nabil and Mardaljevic (2005), "for the vast majority of practitioners, the consideration of any *quantitative* measure of daylight begins and ends with the daylight factor".

The daylight factor is defined as the ratio of the internal illuminance at a point inside the building to the unshaded external horizontal illuminance under a CIE (traditional) overcast sky as given by Moon and Spencer (1942); see section 5.4.1.1).

The simplicity of the measure makes the daylight factor easy to calculate, and it is also intuitively understandable for non-experts. Nevertheless, the simplicity of the daylight factor also results in several shortcomings. As remarked by Reinhart et al. (2006), the daylight factor does not consider season, time of day, direct solar ingress, variable sky conditions, or building location. One of the consequences of this is that the daylight factor is the same for all facade orientations and building locations and therefore, daylight factor investigations can not help in developing glare protection strategies for different facade orientations. Another consequence is that daylight factor investigations provide little or no information about the buildings performance under sunlight conditions.

Furthermore, since the daylight factor is based on the *idealised* CIE overcast sky, any sky condition that deviates from this will potentially affect the interior illuminance levels. Under *real* overcast skies, the measured “daylight factor” has been shown to vary considerably, even for heavily clouded skies (Tregenza 1980).

The daylight factor has been classified as a *static* daylight performance metrics, since it is based on only one (static) sky condition; the CIE overcast sky.

In order to overcome some of the shortcomings of the daylight factor, several *dynamic,* or *climate-based* performance metrics have been proposed. Unlike the conventional static approach, the climate-based approaches employ realistic time-varying sky and sun conditions and predict hourly levels of absolute daylight illuminances in a building. A key advantage of climate-based performance metrics compared to static metrics is that they consider the quantity and character of daily and seasonal variations of daylight for a given building site.

A practical challenge with the climate based approach is the inherent computational complexity. In order to simulate every hour of a working year, several thousand different sky conditions must be considered. In order to reduce the extensiveness of the required computations, the concept of daylight coefficients is often used. Daylight coefficients are mathematical functions that relate the luminance distribution of the sky to the illuminance at a point in a room. The daylight coefficient approach requires that the sky is broken into many patches. The illuminance at a given point in a room that results from a patch of the sky of known luminance is computed and stored. This provides an efficient method for calculating daylight from a number of sky brightness distributions in succession (Tregenza and Waters 1983).

The *Daylight Autonomy (DA*) is one example of a climate-based performance metrics. The daylight autonomy uses work plane illuminance as an indicator for whether there is sufficient daylight in a space so that an occupant can work by daylight alone. The daylight autonomy thus gives the percentage of the year when the minimum illuminance threshold is met by daylight alone. The minimum illuminance threshold used to indicate sufficient daylight is typically 500 lux at the workplane. In 2001, Reinhart and Walkenhorst redefined the daylight autonomy at a sensor location as the percentage of the occupied times of the year when the minimum illuminance requirement at the sensor is met by daylight alone (Reinhart and Walkenhorst 2001).

One of the shortcomings of the daylight autonomy is that it fails to give significance to those daylight illuminances that are below the threshold value. These daylight illuminances might still be valued by the building occupants and might also have the potential to displace electric lighting. Secondly, the daylight autonomy does not provide any information about the occurrence of exceedingly *high illuminances*. This can be of significance because high illuminance levels are often associated with occupant discomfort.

Useful Daylight Illuminances (UDI) is a performance metric that was proposed by Nabil and Mardaljevic (2005) in order to overcome the shortcomings of the

Daylight Autonomy. Useful daylight illuminances are also based on work plane illuminances and are defined as those luminances that fall within the range from100 lux to 2000 lux. As the name suggests, the idea is to determine the occurrence of daylight levels that are useful to the occupant. The UDI scheme provides three metrics; the percentage of the time when the illuminances are within the range defined as useful, the percentage of the time when the illuminances fall short (< 100 lux) and the percentage of the time when the useful range is exceeded (> 2000 lux). According to the originators, the thresholds used are based on a comprehensive review of field studies related to occupant behavior under daylit conditions. The upper threshold is founded on the observation that "*daylight illuminances higher that 2000 lux are likely to produce visual or thermal discomfort, or both*." The lower threshold is founded on the observation that "*daylight illuminances less than 100 lux are generally considered insufficient either to be the sole source of illumination or to contribute significantly to artificial lighting*." (Nabil and Mardaljevic 2006).

A conceptually similar approach was used by Rogers and Goldman in the development of a software used for the evaluation of daylight in classrooms (Rogers and Goldman 2006). Here, two metrics are used; the *continuous* daylight autonomy (DA_{con}) and the *maximum* daylight autonomy (DA_{max}). The continues daylight autonomy gives "full credit" to hours when the work plane illuminances exceed the minimum requirement, as well as partial credit to the hours when the illuminances are below the requirement. For example, when the requirement is 500 lux and the actual illuminance level for a time step is 300 lux, a partial credit of 0.6 (300 lux / 500 lux) is given for that time step. The maximum daylight autonomy is used in order to evaluate the likely occurrence of glare. The threshold for maximum daylight autonomy was defined as ten times the design illuminance of a space. For example, if the design illuminance of a classroom is 300 lux, the threshold value for the calculation of maximum daylight autonomy is 3000 lux. Essentially, this upper threshold gives the occurrence of direct sunlight or other potentially glary conditions such as areas exposed to specularly reflected sunlight. The maximum daylight autonomy can thus provide information about where and how often large illuminance contrasts occur within a space.

2.4.2 Glare assessment methods

Glare is defined as "the condition of vision in which there is discomfort or a reduction in the ability to see details or objects, or both, due to an unsuitable distribution or range of luminances or to extreme contrast in space or time" (CIE 1983).

Two separate forms of glare are identified; discomfort glare and disability glare. Discomfort glare causes discomfort without necessarily impairing the vision of objects, while disability glare impairs the vision of objects without necessarily causing discomfort.

Discomfort glare has received the most focus with respect to the interior working environment. According to CIE (1983), discomfort glare produced by an individual source depends mainly on four parameters:

(i) Source luminance in the direction of the observer's eye.
(ii) the solid angle subtended by the source at the observer's eye.
(iii) the angular displacement of the source from the observer's line of sight.
(iv) the general field luminance controlling the adaption level of the observer's eye.

The *Glare Index* developed by Hopkinson (Hopkinson, Petherbridge et al. 1966; Hopkinson 1972) is based on empirical studies, and takes into account the most important factors which determine the glare discomfort from windows: the luminance of the sky (L_s), the luminance of the interior of the room (L_b), the solid angle of the patch of sky seen (Ω) and the position of this patch of sky in the field of view, given by the position index (P).

$$G = \frac{L_s^{1.6} \cdot \Omega^{0.8}}{L_b \cdot P^{1.6}} \qquad (2.1)$$

According to Hopkinson (1972), "glare can be reduced by cutting down the size and brightness of the visible patch of sky and by increasing the interior brightness by the judicious use of surface areas of high reflectance".

Hopkinson also notes that the exponent on the sky luminance (L_s) is 1.6, whereas that for the average luminance of the interior (L_b) in the denominator is 1. It follows that, all other things being equal, a change in the sky luminance will produce an effect on the Glare Index; the brighter the sky the worse the glare.

However, as the author discusses (Hopkinson 1972), several side effects have significance to the perceived glare, such as the view outside, interior colours, interior reflections, etc. According to Hopkinson, the many side effects serve to illustrate how complex the judgment of discomfort glare from daylighting is.

The formula for glare index by Hopkinson was subsequently modified by Chauvel (Chauvel, Collins et al. 1982) resulting in the often applied *Daylight Glare Index*. For both the Glare Index and the Daylight Glare Index, the perceived glare is classified in one of the following categories: just perceptible, just acceptable, borderline between comfort and discomfort, just uncomfortable and just intolerable.

Several other glare assessment methods have been applied in addition to the daylight glare index. The *Visual Comfort Probability* method has often been used to evaluate glare, especially in North America (IESNA 1984). This method was derived mostly from the works of Luckiesh and Guth (Luckiesh and Guth 1949).

In more recent years, several new glare index formulas have been developed, including the *Unified Glare Rating* (CIE 1995) and the *New Daylight Glare Index* (Nazzal 2001).

Even more recently, the *Daylight Glare Probability* proposed by Weinold and Christoffersen provides a novel assessment of glare by predicting the likelihood of a person being disturbed by glare under a given scene rather than measuring the glare itself (Wienold and Christoffersen 2006).

Nevertheless, the main conclusion remains the same: The perceived glare depends on a complex mixture of both subjective factors as well as measurable physical quantities. In order to make an accurate prediction of the daylight glare perceived by a building occupant, a detailed knowledge of several elements need to be obtained, such as outside sky conditions, window size, reflectance of interior surfaces, eye position, viewing direction, pleasantness of scenery, etc.

2.5 User patterns for manual operation of venetian blinds

Various types of window blinds are regularly applied in office buildings on all continents, and most of these blinds are manually operated. Based on these facts it is surprising that only a few scientific studies concerning the manual operation of blinds have been carried out so far.

One of the earliest studies was conducted in the USA by Rubin, Collins and Tibbott (1978). They investigated the manual switching patterns of interior venetian blinds in about 700 offices at the National Bureau of Standards. The method used was to photograph venetian blind positions in the offices at different times of the day and year. One of the conclusions from this study was that occupants did not change blind positions within a day. The authors suggest that the occupants' preference for window blind position is based on long-term perceptions of solar radiation, and changes within a day are essentially ignored.

Rea (1984) followed with a study at the Brooke Claxton building, a 16-storey office building in Canada. Rea used external photographs and related the blind positions to the incident irradiance. According to Rea, the results from this study, as well as the study of Rubin, indicates that occupants use venetian blinds to prevent direct sunlight or thermal radiation, or both, from entering into the interiors.

Inoue et al. (1988) studied the manual control of venetian blinds by taking photographs of the facades of four high-rise office buildings in Japan. A major finding of this study was that, beyond a threshold value for direct solar radiation of about 50 W/m^2, blind occlusion is proportional to the solar penetration depth into a room.

Lindsay and Littlefair (1993) carried out similar investigations with video camera recordings of five different office buildings in England. Unfortunately, the camera resolution was too low to record the tilt positions of the blind slats. Based on the results, the authors found it likely that glare rather than heat was the main motivating factor causing the blinds to be moved.

Bülow-Hübe (2000) studied the user operation of exterior venetian blinds by fifty office workers in Sweden. One of the findings was that positive slat angles (tilt towards the exterior ground) were strongly preferred to negative ones. The most common slat position was a positive tilt of 46˚-60˚ (from the horizontal), and in this position the view out through the blinds was very limited. Nevertheless, according to comments on a questionnaire, some of the office workers claimed that in operating the blinds they made a compromise between glare and the possibility to see out: they would have been more comfortable with the lighting situation if they had pulled down the shade even more, but they chose a more open position in order not to loose too much of the view out.

Foster and Oreszczyn (2001) used a video camera to examine the use of venetian blinds in three fully glazed office buildings in England. They estimated the occlusion index by considering both the blind position and the slat angle. The results indicated no clear relation between the degree of occlusion and the degree of sunshine affecting each facade. This result was unexpected, and the authors suggest a possible explanation in that blinds tend to be fixed at a certain level as there is not much blind movement over the week, although the sunshine level did change significantly over the periods of measurement. The results from this study showed that the average occlusion level over all facades studied was about 40%.

The behavioural patterns that govern when and how office occupants use their manual or automated electric lighting and blind controls were studied by Reinhart and Voss (2003). As a part of this work, a field study was carried out in 10 daylit offices in Germany with automatically controlled external venetian blinds with manual override. In the discussion of the manual control of blinds the complexity of blind operation is addressed: "Blinds serve diverse purposes. They often act as a combined heat and glare protection device to maintain adequate visual and thermal comfort conditions under sunny ambient sky conditions, and/or to reduce the cooling loads. Blinds are also employed to provide visual shelter i.e. privacy for the users." The results from this study supported the findings of Inoue et al. (1988) in that direct sunlight needs to lie above 50 W/m^2 to cause glare and trigger the people to lower their blinds.

A later pilot study by Sutter investigated the use of remotely controlled black venetian blinds in eight offices with VDU screens in France (Sutter, Dumortier et al. 2006). The blinds were located in the view opening (below and above eye level). After one to two months of monitoring, it was observed that several of the eight subjects showed very different behaviour with respect to the use of the blinds.

The study tested several hypotheses and resulted in several important conclusions. The first main conclusion is the following: “The users with a better quality screen tolerated higher veiling reflections, allowing them to take more advantage of the amount of daylight available”. This finding indicates that applying high luminance VDU screens might be part of a strategy to improve daylight quality in VDU offices. In this study a commonly used luminance ratio rule of thumb was also tested. This rule states that luminous ratios between the task, the surrounding zone and the non-surrounding zone must be within 1:3:10 to provide good visual comfort and performances. The results indicated that the subjects positioned their blinds in such a way that the luminances were in 1:3:10 ratio as long as no source of daylight was visible in the users’ field of view. However, if a window was part of the field of view, the luminances were in a 1:6:20 ratio, rather than a 1:3:10 ratio. If the patch of bright light remained relatively small, it was observed that a luminance ratio of up to 1:50 could be tolerated. This supports previous findings that users tend to accept significantly higher luminance ratios from daylight sources than from electric lighting.

The same pro-daylight conclusion was drawn from the studies of glare: With a window in the field of view the tolerance to glare was higher than in situations without a window present.

The investigation of preferred venetian blind position is another important contribution from Sutter’s study. With only eight subjects it is not advisable to draw general conclusions, yet it is interesting to note that the blinds were completely raised on average only 17.7% of the time. Intermediate blind positions were recorded 6.5% of the time, while the blinds were completely lowered on average 74.8% of the time. Also the slat tilting of the lowered blinds was recorded. 50.9% of the time the blinds were completely down with a positive tilt (towards the exterior ground). 20.1% of the time the blinds were down with a horizontal tilt, and 4.8% of the time the blinds were down with a negative tilt (towards the exterior sky).

Sutter gives two explanations for the infrequent use of negative blind tilts: firstly, negative tilts will not block direct sunlight, and secondly the view towards the outside [ground] is obstructed.

The studies discussed above are at some points slightly contradictory and not always statistically significant. Yet, it seems clear that different users have different behaviour with respect to the use of window blinds. It also seems like the individual behaviour is consistent and not arbitrary. The studies also showed that subjects tend to lower or raise their blinds only when the lighting conditions (given by the external vertical global illuminance or the window luminance) change significantly, by a factor of about 2 or 3. In other words, the users waited until the level of daylight in the office was very low before raising their solar protection. This result strongly indicates that it is possible to utilise significantly more daylight with automatically controlled shading systems than with manual controls. The way blinds are operated will influence the energy consumption of a building. This factor should be taken into account in the planning process. It seems clear that from an energy-perspective, automatic blind control could be very beneficial. Even though the preferences are individual, the behaviour with respect to blinds is relatively consistent for each occupant. Therefore, it should be possible to generate individually adapted control algorithms for the blinds that also provide the necessary user comfort. In fact, it is reasonable to conclude from the studies that most occupants are reluctant to change the blind position unless they really feel uncomfortable, perhaps because this action requires an extra effort. Therefore, an individually adapted blind control algorithm should have the potential to enhance both user comfort as well as energy savings.

2.6 Energy savings from utilisation of daylight

Daylight can be utilised to save energy for electrical lighting by dimming or switching off the electric lights. Daylight responsive systems that regulate the electrical lighting according to available daylight are used increasingly often in office buildings. Several studies have tried to quantify the saving potential by applying such control systems in office buildings.

2.6.1 Studies on energy savings from utilisation of daylight

Zonneveldt and Rutten (1993) investigated the lighting energy saving potential for different control strategies of electric lighting in the Netherlands. A computer based model was used to predict an energy saving potential of 30% for Dutch office buildings, as compared to the praxis of constantly keeping lights on during office hours.

Opdal and Brekke (1995) investigated potential lighting savings in 10 offices in Trondheim, Norway. Measurements conducted over a full year indicated a saving potential of about 30% for a lighting control system producing constant lighting levels. Computer simulations of the same offices predicted a saving potential of just over 40%.

Embrechts and Van Bellegem (1997) argue that centralised control systems often cause annoyance and complaints and dissatisfied users might sabotage such disturbing control systems. Therefore, they investigated systems that control the lighting individually for each luminaire. Monitoring such systems at different test sites for a period of almost two years showed that energy savings in the region of 20% to 40% could be expected.

Li et al. (2006) investigated the lighting savings obtained by using dimming controls for the lighting in an open plan office at the City University of Hong Kong. The monitored room was facing northwest and equipped with ceiling mounted recessed fluorescent luminaries. The mean interior illuminance from the electric lighting installation was 480 lux (close to the recommended value of 500 lux). Using high frequency controls it was not possible to dim the light to full extinction; it was reported that most dimming ballast could reduce the light output to less than 20% of maximum output. However, as noted by the authors, such system operation may be less noticeable and less annoying to occupants. The test was carried out for a period of 7 months, from February to August 2004. Based on the results the annual savings in electric lighting under dimming control was estimated to 33%.

Galasiu et al. (2007) conducted an interesting field study on daylight responsive lighting controls in an open-plan office. Here, three different lighting energy saving methods were investigated: i) occupancy sensors, ii) daylight responsive light sensors and iii) individual dimming control. The test was carried out in Burnaby, Canada, and a total of 86 workstations with suspended direct-indirect luminaires were monitored for a test period of one year. The results from this study indicated the following lighting energy savings if the three control methods had been installed separately: 35% for the occupancy sensor, 20% for the daylight responsive light sensors and 11% for the individual dimming control. The authors noted that greater savings from daylight dimming would have been possible by allowing the downlights to dim to zero instead of only to 50% output, and also by controlling the uplights in addition to the downlights. The authors also registered the blind use throughout the study and reported a high average blind occlusion of the facades of 55%. “Clearly blind use may strongly affect energy savings with such controls”.

The five studies referred to above all reported lighting energy savings in the range from 20% to 40% simply by dimming or switching off electrical lighting according to available daylight. It is clear that the actual savings will depend on many factors such as facade orientation, building location, window to floor area, the type and use of shading, etc. In the studies referred to above, no particular attention was put on regulating or enhancing the amount of available daylight. The first step in such an approach is to apply automatic management of the shading system.

A field study in Ottawa (Canada) investigated the effect of daylight responsive lighting controls in combination with window blinds in four adjacent south-facing private offices (Galasiu, Atif et al. 2004). The test was carried out for a period of one year, and the results showed that under clear skies and without window blinds present, the lighting control systems reduced the lighting energy consumption by as much as 50% to 60% when compared to lights fully on in the time period from 06.00 to 18.00. However, this situation without shading is not very realistic. On the contrary, as noted by the authors, “research shows that occupants are very likely to change the position of the blinds when direct sunlight reaches their work area, but seldom change them for useful daylight admittance even after the unwanted conditions fade away”. Therefore, in this study the impact of several different blind positions was investigated. For static blind positions, the energy savings were reduced by 5% to 80%, depending on the blind position. The savings in lighting energy increased when photo-controlled blinds were used instead of manual blind control. As explained by the authors, “this was because the photo-controlled blinds were able to adjust their slats periodically according to the variations in external daylight levels”.

In a field study by Lee and Selkowitz (2006) both the electrical lighting as well as the shading system was automatically controlled. The study was conducted for a period of 9 months in a 401 m^2 unoccupied, furnished mock-up in New York. Two areas were investigated; in area A the automated roller blinds were controlled to reduce window glare and increase daylight, while in area B the automated shade was controlled to block direct sun. Area A and B also differed in that area A was sidelit and area B was bilateral daylit. Lighting energy savings in the period from mid-February to September 21st compared to a non-daylit reference were reported. For area A the average savings in the 7 m deep dimming zone was 20% to 23% depending on the lighting schedule. The average savings for area B was 52% to 59%. The authors noted that without active shade management the energy savings would have been significantly lower due to non-optimal control by the occupants. It should also be noted that standard roller shades were used in this field test, and that these are developed primarily for shading purposes and not with the aim to utilise daylight.

A field study in Lund (Sweden) monitored offices with motorised interior venetian blinds and daylight responsive electrical lighting (Bülow-Hübe 2007). The monitored offices were sidelit and 4 m deep. The white venetian blinds were modified so that the upper section had slats in a more open position for added daylight transmission. The venetian blinds were controlled to avoid direct sunlight. The blinds were automatically lowered when vertical luminances exceeded 20 klux, and for luminances below 15 klux the blinds were automatically raised after a delay of 30 minutes. The reported electric lighting savings, compared to a non-daylit office were 5% in November and 77% in May. The average savings over a year were estimated to 50%.

The field studies in Ottawa, New York and Lund with automated shading and daylight responsive lighting indicates that lighting savings of at least 50% can be obtained with automated solutions compared to traditional lighting solutions that do not take advantage of daylight. These significant savings can be obtained without applying shadings systems specially designed for daylight utilisation, such as the daylight redirection systems discussed in chapter 3.

2.6.2 Method to predict energy savings from daylight

It has been shown that for daylight through windows, the saving potential depends on the type of solar shading used and the operation of the solar shading. Assuming that the solar shading is operated to prevent glare and overheating, two important factors that determine the daylight harvesting potential through windows is the size of the window (relative to the perimeter floor area) and the light transmission properties of the window.

This is the basis for an interesting simplified method to predict energy savings proposed by Krarti (2005). He defines the *daylight aperture* as a function of window to perimeter floor area (A_{win}/A_{per}) and window transmittance (τ_{win}). For small daylight apertures, as illustrated in Figure 2-3, the energy saving potential increases almost linearly with window area and window transmittance. Note that the energy saving potential is quite large also for relatively high latitudes.

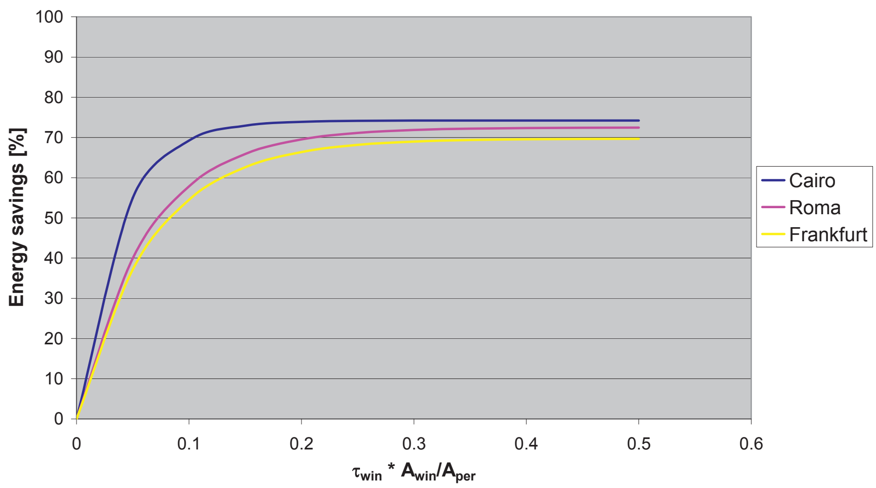


Figure 2-3 A simplified model by Krarti shows that lighting energy saving from utilisation of daylight through windows depend strongly on window area and window transmittance. Graph made for energy savings in a perimeter area that is 2.9 m deep according to numbers provided by Ihm, Nemri and Krarti (2009).

The energy saving potential given by Krarti (2005) is calculated for a vertical window opening without any daylight redirecting components. Therefore, the daylit zone where significant energy savings can be obtained is limited to a short distance from the window wall. However, with the application of daylight redirection systems (discussed in chapter 3), the daylit zone can be significantly increased. Daylight redirection systems also enable better utilisation of the direct sunlight component of the daylight. In the simplified model by Krarti direct sunlight is mostly excluded through the use of window blinds and contributes little to the energy saving potential.

2.6.3 Summary of field studies

The method proposed by Krarti emphasises the importance of the daylight aperture; given by the window transmittance (τ_{win}), the window area (A_{win}) and the floor area of the perimeter zone (A_{per}). For some of the field studies discussed above, enough information was provided in order to calculate the daylight aperture. The main results for these four field studies are summarised in Table 2-2.

The reported savings should only be taken as rough estimates to indicate the saving potential that can be expected. It is important to realise that several factors affect the energy savings; including the orientation of the facade, the daylight aperture (as given by Krarti), the depth of the area to be lighted, the type of shading system (or daylight redirection system) that is applied and also the type of lighting control system. For example, the study by Opdal and Brekke (1995) showed that an on/off lighting control gave very small savings on a north oriented office in Trondheim, while it was quite effective in a south oriented office.

Table 2-2 Lighting energy savings from utilisation of daylight.

Ref.	Location	Daylight aperture*	Area depth	Shading system	Lighting control system	Annual lighting energy savings
Ihm 2009	Boulder, USA	0.105	2.9 m	Auto-matic interior shades	Dimming (500 lux)	All orien-tations: 64%
Opdal 1995	Trondheim, Norway	0.101	4.25 m	Manual curtains / blinds	Dimming (500 lux)	South: 29% North: 22.5%
					On / off 500 / 900 lux	South: 35% North: 2.5%
Lee 2006	New York, USA	0.077 – 0.135	7.0 m	Auto-mated roller blinds	Dimming (500 lux)	West: Feb. to Sept; 23%
Bülow -Hübe 2007	Lund, Sweden	0.195	4.1 m	Auto-mated interior white blinds	Dimming (500 lux)	South: May: 77% Nov.: 5%

* The daylight aperture is defined as: τ_{win} (A_{win}/A_{per})

2.6.4 Global energy savings

Daylight entering into a building can also affect the cooling and heating loads. These savings will not be discussed in detail here but one study addressing the global energy savings from utilisation of daylight will be mentioned:

Bodart and De Herde (2002) used computer simulations to predict the lighting energy savings as well as the global energy savings by utilising daylight in Belgian office buildings. The simulations indicated global energy savings of about 40% for the type of glazing normally used in office buildings in Belgium.

2.6.5 Conclusions on energy savings

It can be concluded that the energy savings from utilisation of daylight can be quite significant. Furthermore, the utilisation of daylight in buildings can be considered as a three-step process.

1. The first step to reduce lighting energy consumption is to apply *daylight responsive dimming*. Lighting savings from 20% to 40% can be expected. This first step cannot really be considered as a daylighting solution but rather as a measure to improve the efficiency of the electric lighting system by taking advantage of available daylight.

2. The second step is to apply *automated shading solutions* in combination with the daylight responsive lighting controls. This can reduce or eliminate the negative effects of sub-optimal manual operation of the shading system. Potential lighting energy savings of at least 50% can then be expected compared to an installation that does not take advantage of daylight.

3. The third step is to also apply *daylighting systems* that are specially designed to utilise available daylight. A review of daylight redirection systems aimed at utilising daylight entering through a vertical window opening is given in chapter 3. So far, the extra energy savings that can be expected from applying daylighting systems compared to standard shading devices are not well documented in the literature.

The expected savings reported above should only be taken as rough estimates. It is important to realise that several factors affect the energy savings, including the orientation of the facade, the daylight aperture (as given by Krarti), the depth of the area to be lighted, the type of shading system (or daylight redirection system) that is applied (including control system) and also the type of lighting control system.

2.7 Other economic considerations

The utilisation of daylight through vertical window openings in office buildings has several economic implications. Firstly, as discussed in the previous section, daylight through windows will influence the energy consumption of the building, affecting not only the energy usage for electric lighting but also the cooling and heating loads.

A second factor that has received increasing attention is the effect of windows and daylight on the office workers well-being. Improved daylight quality can influence the health and productivity of the office worker, and such positive effects have potentially large economic implications.

Finally, the cost of delivered lighting also provides a strong argument for utilising daylight through windows, as shown in the following section.

2.7.1 Cost of delivered lighting

The costs associated with various lighting and daylight harvesting techniques have been assessed in a study by Fontoynont (2009). Here the long term costs were calculated and the different lighting techniques were compared on the basis of average illumination delivered on the work plane per year, as shown in Figure 2-4.

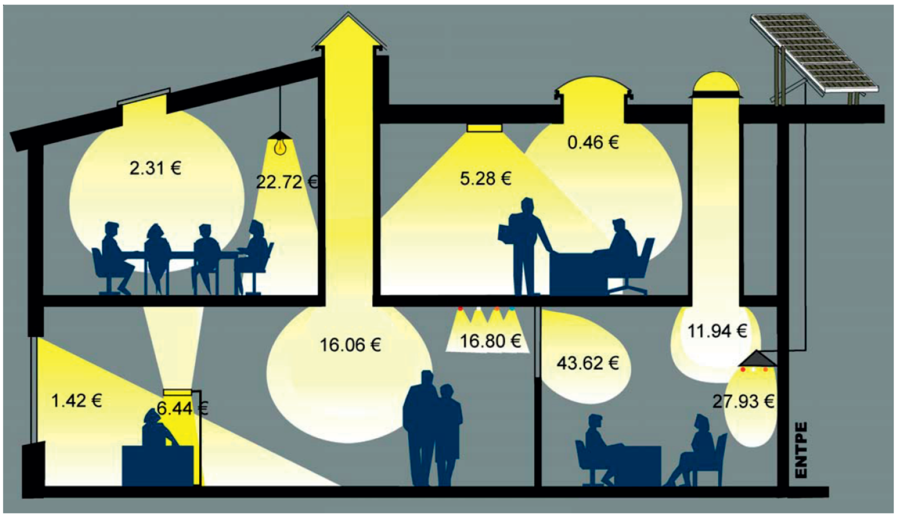


Figure 2-4 Cost of providing light on the working plane by different means. The cost includes the cost of initial construction and operation/maintenance for the expected lifetime of a building prorated on an annual basis (€/Mlmh). Illustration reprinted from Fontoynont (2009).

The selected daylighting techniques given are: roof monitors, north oriented facade windows, borrowed light windows, light wells, daylight guidance systems as well as off-grid lighting based on LEDs powered by photovoltaic's. The electric lighting installations given are; fluorescent, tungsten and LED.

The results showed that different daylighting techniques deliver light with a significant difference in cost. Daylight delivered through vertical window openings is the second most cost effective solution. Daylight through vertical windows is about 4-5 times less costly than light from a standard electrical installation. Daylight through rooftops can be provided with even lower costs.

The given costs are calculated for the climate of Lyon (France). As noted by the author, the given data are highly dependent on the hypothesis which was defined related to factors such as: the climatic conditions, the latitude, the uniformity of the light distribution, the daily lighting schedules, the duration of the systems, etc. Also it should be noted that the various solutions are not directly comparable. For example, electric lighting installations are much easier to control and can meet lighting needs both day and night. On the other hand, facade windows provide not only lighting but also a potential for contact with the exterior surroundings, an attribute that is known to be highly desired.

2.7.2 Lighting and productivity

The previous section showed that significant energy savings can be obtained by utilising daylight in buildings. However, the costs associated with lighting energy are very small compared to the total costs for work. Fontoynont (2002) estimates the lighting costs to about 0.1% of the total costs for work in offices, and the lighting costs are even less in factories where capital-intensive machines are present. From this it is clear that even a small positive effect in productivity can justify most changes in lighting.

Juslén and Tenner (2005) discussed the mechanisms that might be involved with respect to human performance and lighting. Their 10 mechanisms that can increase performances are:

1. *Visual performance*. When people can see the task better, they can perform better.
2. *Visual comfort*. Decreasing discomfort glare influences performance because of increased concentration.
3. *Visual ambience*. Lighting influences visual ambience, which being part of the working environment, influences performance.
4. *Interpersonal relationships*. How people see each other influences how they feel about each other, which influences co-operation and productivity.

5. *Biological clock*. Light adjusts the biological clock, which controls the circadian rhythms and thus influences performance at certain times.

6. *Stimulation*. Light stimulates psychological and physiological processes, which enhances performance.

7. *Job satisfaction*. Improving lighting conditions might increase job satisfaction via task significance and autonomy, which influences performance.

8. *Solving problems*. Solving existing lighting problems, which are complained about, increases well-being and motivation, which enhances performance.

9. *The halo effect*. The effect of the belief in the superiority of a new technology or product itself might result in enhanced performance.

10. *Change process*. Good change management increases the positive effects of the lighting change and diminishes negative effects.

A large number of studies have been conducted to establish the relationship between task luminance and performance. Many of the studies were conducted in the period from 1920 to 1970, and a summary of the results from these studies are provided by Juslén and Tenner (2005). Since the lighting practice has changed significantly in the last decades, only two of the more recent studies will be discussed in the following.

Van Bommel et al. (2002) investigated the effects of illuminance levels in the metal industry; on task performance, on number of rejects and on accidents. Their main conclusion was that total productivity increased by about 8% when the lighting levels increased from 300 lux to 500 lux. An increase from 300 lux to 2000 lux gave a productivity increase of about 20%. It should be noted that the reported statistical variance was quite large in this study.

Juslén, Wouters and Tenner (2007) conducted a field study for a period of 16 months in a luminaire factory in Finland. Prior to the study the lighting on each work station consisted of the general lighting that provided a horizontal illuminance of 100 – 380 lux and a non-dimmable task-lighting system that created, together with the general lighting, a horizontal illuminance of approximately 700 lux. During the study the workers were given the opportunity to individually control their task-lighting up to a maximum of 3000 lux on top of the general lighting. A reference group continued to use the standard non-dimmable task-lighting system. The study showed that workers systematically increased the lighting levels when given the opportunity, but with large individual differences. The average preferred illuminance was 1181 lux or 1359 lux, depending on the dimming speed. The increase in productivity when the workers were allowed to control the lighting at their workstation was 4.5% on average. The authors did not conclude whether this increase should be attributed to visual performance, biological effects or psychological effects.

As discussed by Juslén and Tenner (2005) one should keep in mind that in experiments on human performance an increase of productivity could be caused by the so-called Hawthorne effect. The Hawthorne effect is the effect that the study or evaluation itself has on people; the feeling of being observed and cared for can lead to improved performance. It is clear that new studies will be required to better document the productivity increases that can be expected from changes in lighting and taking measures to eliminate the Hawthorne effect. Also, considering the potential importance of the biological effects of lighting, studies of productivity related to daylight or daylight-like electrical lighting should be undertaken. However, it seems clear that improved lighting conditions can lead to lasting productivity increases that can justify significant investments aimed at improving both the electrical lighting as well as the utilisation of daylight.

2.8 Summary and conclusions

Windows and daylight are highly appreciated by the building occupant. The main attribute of windows is the possibility for contact with the exterior surroundings. Daylight through windows is strongly preferred over electrical lighting. In the past, this could be attributed to negative aspects of electrical lighting such as the light flickering caused by the magnetic ballasts. Today, as electrical lighting has improved, other explanations for the continued preference for daylight must be considered. One of these explanations is the biological effect of light. The literature shows that today's electrical lighting requirements are not set to meet biological lighting needs, and the long recognised belief that daylight supports better health has only recently been approved by science.

The literature shows that manual window blinds are operated sub-optimally, both with respect to daylight quality as well as with respect to energy saving potential. Most building occupants seem reluctant to change the blind position unless they really feel uncomfortable. For this reason, automated blinds can improve not only the energy saving potential, but also the user comfort, especially if an advanced and individually adapted blind control algorithm is used.

The two main economic benefits from utilising daylight through window openings are energy savings and increased productivity. Field studies suggests that lighting energy savings of at least 50% can be expected in the perimeter zones of a building by taking full advantage of available daylight, as compared to an installation that does not take advantage of daylight. The economic benefits from increased productivity might be even more important, but these benefits are less documented.

The costs for delivered lighting vary significantly as a function of the lighting technique. Daylight delivered through vertical window facades constitutes one of the most cost-effective lighting techniques available today.

Several different methods are used in order to assess daylight in a building, in particular illuminance-based methods, various glare assessment methods as well as guidelines based on luminance ratios or average window luminance. The continuous search for new methods underscores the complexity of daylight assessment in buildings.

In the next chapter, an overview of different types of daylight redirection systems is given, as well as a discussion related to the efforts to assess the performance of such systems.

3 Daylight redirection and shading systems

The pursuit of perfection, then, is the pursuit of sweetness and light.

Matthew Arnold

3.1 Introduction

In the previous chapter it was argued that the possibility for outdoor viewing and daylight supply to the interiors are two of the most positive aspects associated with windows. However, as noted by Kim and Wineman (2005), windows do not always add desirability. “For example, though large windows with their views to the outdoors are generally considered assets in buildings, large windows are associated with several thermal and visual liabilities such as solar heat gain during the day, heat loss at night in winter, and more importantly, glare that can cause both visual disability and discomfort”.

Advanced fenestration systems are used to reduce the thermal and visual discomforts associated with windows. Preferably this should be achieved without diminishing the positive attributes of windows, including the possibility for viewing and daylight supply. Two of the most important types of fenestration systems are daylight redirection systems and shading systems.

Daylight redirection systems are used mainly to utilise daylight supply and to improve visual comfort. The main function of such systems is to redirect sunlight and/or diffuse skylight deeper into the interiors via the ceiling.

The incident light can be characterised by its elevation angle and azimuth angle (see section 4.2). All daylight redirection systems have the ability to alter the elevation angle of the incident light. In addition, some systems can also alter the azimuth angle of the incident light.

In this way the uniformity of the illuminance distribution in the interiors is improved, contrasts are reduced and the room appears less gloomy. The benefits of improved daylight distribution are twofold: (i) increased energy saving potential by reducing the need for electric lighting and (ii) improved lighting quality and visual comfort for the building occupant.

Solar shading systems are used primarily to protect against thermal discomfort from overheating, but these systems can also contribute to glare protection. In general, exterior systems provide the best overheating protection. However, architects are sometimes reluctant to use exterior solutions that alter the expression of the building facade. With careful design interior systems or systems located between window panes can also provide adequate overheating protection.

In this chapter some examples of advanced fenestration systems are discussed. The main focus is on different types of daylight redirection systems, but it should be emphasised that some fenestration systems can provide good solutions for both daylight redirection and solar shading. Therefore, for some systems it is a matter of choice whether they should be regarded primarily as daylight redirection systems or shading systems.

The discussion that follows here is limited to systems that can be applied in vertical windows and are confined to the facade area. The focus is on interior systems or systems that are integrated between window panes. This means that systems that apply various solutions that extend into the building interiors in order to guide and distribute daylight to the core of the building are not covered here. Also, systems that let light into the building via the rooftop are not covered.

3.2 Optical principles relevant for daylighting

Daylight redirection systems rely on the optical principles of reflection, refraction or diffraction to alter or enhance the distribution of incoming daylight. In this section the main optical principles and their importance for the performance of daylight redirection systems are discussed briefly. This section can thus be regarded as background information for the following discussion of daylight redirection systems.

The daylighting properties of a material can be related to what happens when light is incident onto the material. Figure 3-1 shows a schematic illustration of this situation, with light of intensity I_i incident on a material surface at an angle θ_i. The light is partly reflected from the surface and partly transmitted through the sample. The reflected light can be scattered (I_d) or specularly reflected (I_s) as indicated in Figure 3-1. The transmitted light (I_t) can be directly transmitted as shown in Figure 3-1, or diffusely transmitted (not shown in the figure). Light that is not reflected or transmitted is absorbed in the material.

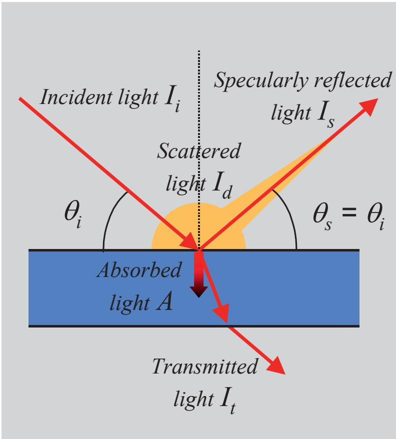


Figure 3-1 Schematic illustration of how light interacts with matter.

3.2.1 Absorption

Light that is not reflected or transmitted is absorbed in the material. Absorbed light is converted to heat that is radiated from the material. A colour appears when the material absorbs selectively in the visible region. In the following it will generally be assumed that the slat materials are colourless, with a constant absorption, independent of wavelength.

3.2.2 Refraction

Refraction occurs as light passes the boundary between two materials with different refractive indices. For example, when direct sunlight enters a pane of glass the direction of the light within the glass will be altered by refraction, as illustrated in the figure below. As the light exits the glass the direction will again be altered, and this time in the opposite way back to the original direction, thus providing a clear and undisturbed view through the glass pane.

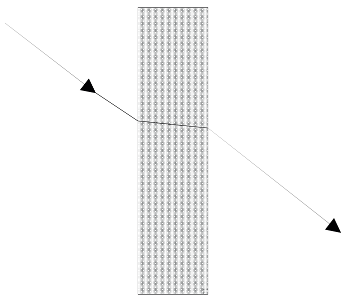


Figure 3-2 Illustration of refraction at the boundary for light passing through a pane of glass.

3.2.3 Surface reflection

Light that is incident on a surface can be reflected specularly or scattered, resulting in diffuse reflection.

Specular (or regular) reflection is characterised by reflectance in the mirror direction of the incident direction; that is the angle of specular reflectance (θ_s) equals the angle of incidence (θ_i).

Diffuse reflection refers to a diffusion of light where, on the macroscopic scale, there is no specular reflection. Uniform diffuse reflection is a special case of diffuse reflection in which the spatial distribution of the reflected radiation is such that the luminance is the same in all directions in which the radiation is reflected. Materials that reflect incoming light in this way are called Lambertian diffusers. Depending on the reflectance values, diffuse materials can be characterized as white, grey or black.

Most opaque materials produce a combination of specular and diffuse reflection. This type of reflection is known as mixed reflection.

Total internal reflection is a special mechanism of reflection. This can occur (for oblique angles of incidence) at the boundary between materials with different indices of refraction. Total internal reflection can only occur when light is propagating within the material with the highest refractive index. Total internal reflection is a very efficient reflection mechanism in that 100% of the light is reflected.

Total internal reflection should not be confused with total reflectance. Total reflectance is the total amount of reflected light (specular + diffuse) relative to the amount of incident light:

$$\rho_{tot} = \frac{I_s + I_d}{I_i} \tag{3.1}$$

3.2.4 Retro-reflection

A material can be designed in such a way that the incident light is reflected back in the direction of incidence. Such materials are called retro-reflectors. Retro-reflectors can be produced by several different methods. One example is the application of glass spheres within the retro-reflecting material or device. Here, retro-reflection is accomplished by a combination of refraction at the front surface of the sphere and specular reflection at the back surface, which is sometimes mirror-coated for improved performance.

This type of reflectance mechanism is often used to obtain retro-reflectance in materials or devices used to improve traffic safety. The same mechanism is also known from nature in the cat's eye.

3.2.5 Transmission

Light that is transmitted through the material can be regularly transmitted or diffusely transmitted. Regular transmittance is necessary to provide a clear view through the material.

3.2.6 Diffraction

Diffraction is a mechanism that can alter the direction of light as it passes a sharp edge (slit, hole, etc.). The principle of diffraction is utilised for daylighting in so-called holographic optical elements.

3.2.7 Optical properties of venetian blinds

Venetian blinds for interior applications are available in a multitude of colours and surface finishes. The most common surface finish is white and nearly diffuse. To reduce glare problems, some blinds have different optical properties on the two surfaces, e.g. high reflectance white or specular on the upper surface and black or grey on the lower surface. As shown by Rubin et al. (2007) and illustrated in Figure 3-3, the reflectance can vary with wavelength.

The figure also shows the total and diffuse reflectance properties of different coloured venetian blinds. The white blind has a total reflectance of about 75% (at 550 nm) that is mostly diffuse. All the other finishes are less reflective. The metallic blind is characterised by a total reflectance of about 60% and a diffuse reflectance of about 45%.

It is here of interest to note that the visible range of the spectrum is from about 380 nm to 780 nm, while the solar energy spectrum at the surface of the earth extends from about 300 nm to 2500 nm.

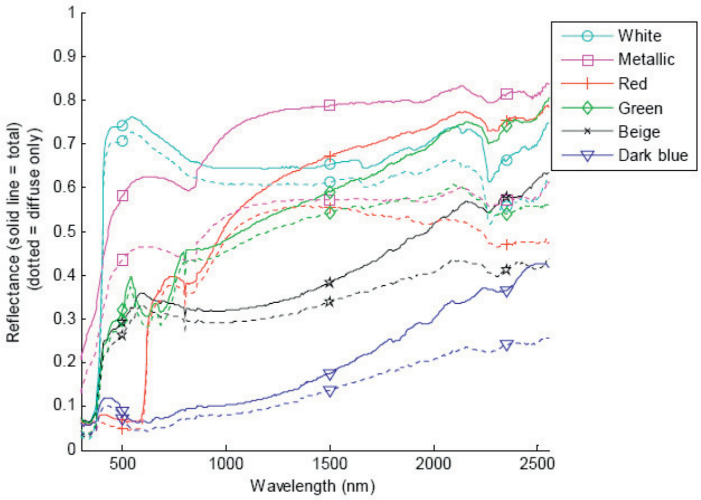


Figure 3-3 Total reflectance and diffuse reflectance for venetian blinds of various colours. Illustration reprinted from (Rubin, Jonsson et al. 2007).

Similar results were obtained in measurements carried out by Nilsson and Jonsson (2010). Results for blinds with white slats and silver slats are shown in Figure 3-4.

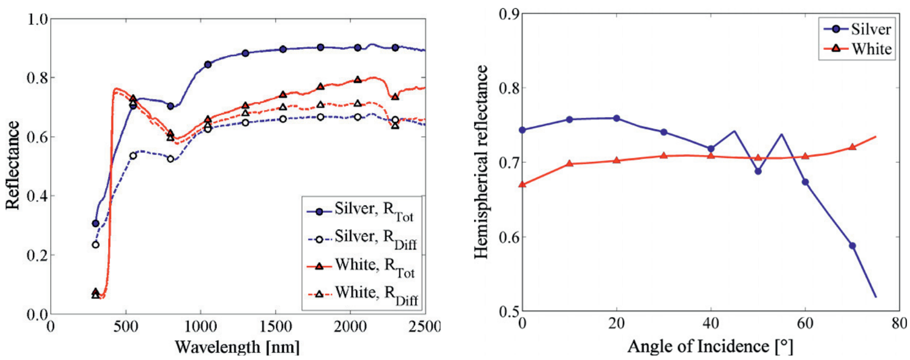


Figure 3-4 Reflectance of blinds with white slats and silver slats. Left: Total reflectance and diffuse reflectance as a function of wavelength. Right: Total reflectance at 633 nm as a function of incidence angle. Illustrations reprinted from (Nilsson and Jonsson 2010).

Blinds for daylight redirection are typically made of materials that are more specular than the metallic blinds in Figure 3-3 and the silver blinds in Figure 3-4.

One example of available materials for such blinds is the aluminium reflector materials from Alanod GmbH. According to the website of Alanod, two of the most reflective specular materials are Miro 2 and Miro Silver 2. These materials have a total reflectance of 95% and 98% respectively (measured according to DIN 5036-3). For both materials the diffuse reflectance is given as less than 5%, indicating that the materials are highly specular with an appearance as that of a mirror.

3.3 Louver and blind systems

Louver and blind systems are commonly used in office buildings. Traditional louver and blind systems are used primarily for solar shading, to protect against glare and for privacy. More sophisticated louver and blind systems are designed to function also as daylight redirection systems.

Louvers and blinds are normally composed of multiple horizontal slats, but also vertical or sloping slats are known. The slats can be either fixed or tiltable. Louvers and blinds can be located on the exterior side or interior side of a window or skylight, or between the panes of a multiple glazing unit. In this review the discussion is limited to solutions with horizontal slats applied to vertical window openings.

The term louver normally refers to exterior systems. Louvers are typically made of galvanised steel, anodised or painted aluminium, or plastic for high durability and low maintenance. The term blind normally refers to interior systems or systems located between window panes. Interior venetian blinds for commercial buildings are normally made of plastic or painted aluminium. The slats are typically either flat or moderately curved. The slats are usually evenly spaced at a distance that is smaller than the slat width so that the slats will overlap when the blinds are fully closed. Interior slats are usually from 10 mm to 50 mm wide; exterior slats are usually from 50 mm to 100 mm wide.

Louvers and blinds are in general very flexible systems that can be useful in a number of applications and under varying conditions. A number of sophisticated shapes and surface finishes have been designed to tailor the performance of the systems with respect to specific needs. In the following sections different types of systems designed for daylight redirection and/or shading are described.

3.3.1 The daylight redirecting blind system

The basic form of the daylight redirecting blind system can be obtained by turning the slats of a conventional venetian blind system upside down, so that the resulting concave curvature admits daylight and redirects it towards the ceiling. If it is desired to redirect as much daylight as possible, the upper surface of the slats should be highly reflective and have a relatively specular surface finish. To avoid glare, redirecting louver systems are normally located in the upper (clerestory) part of the window opening, above eye level of the building occupants. The slats can also be perforated to admit some daylight and provide a limited view out, even when the blinds are fully closed.

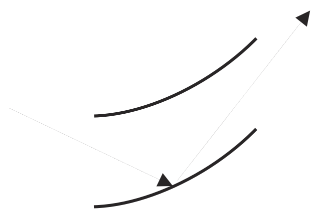


Figure 3-5 Schematic illustration of the basic daylight redirecting louver system.

3.3.2 The Fish system

The Fish system is an innovative blind system consisting of fixed horizontal slats. The slats in the Fish system are solid, with a triangular cross-section resembling that of a fish bone. The system is designed to redirect diffuse light, improve daylight distribution, and reduce glare. The special shape of the slats is designed so that light with high elevation angles is transmitted and redirected towards the ceiling of the room, see Figure 3-6. According to Ruck, Aschehough et al. (2000), the system without the glazing theoretically transmits 60% of diffuse light for an aluminium surface with a reflectance of 85%. The Fish system is not very effective as a solar shading system, and therefore additional shading might be required for overheating protection.

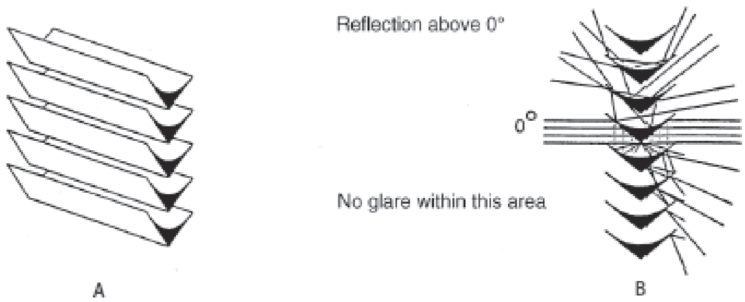


Figure 3-6 The Fish system consisting of fixed horizontal slats. The cross-section of the slats (shown in black) resembles that of a fish bone. Note that the incoming light is from the right in this illustration. The incoming light produces very little downward directed light within the interiors. Illustration reprinted from Ruck, Aschehough et al. (2000).

3.3.3 The Okasolar system

The original Okasolar system is also a fixed system, consisting of numerous equally spaced three-sided slats located inside a double glazing unit. The system is designed to transmit and redirect sunlight up towards the ceiling in the winter season, while high-angle light is not transmitted, giving a shading effect in the summer season. This principle of operation is illustrated in Figure 3-7. According to Ruck, Aschehough et al. (2000), the system can be tailored in order to suit the latitude where it will be used. However, the operating principle of this system does not seem to be well suited to provide overheating protection at high latitudes, where the summer sun is often incident from a relatively low solar elevation.

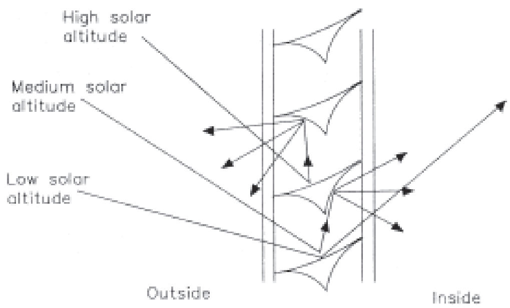


Figure 3-7 The Okasolar system consists of fixed equally spaced reflective slats. Sunlight incident from a low altitude is transmitted, while sunlight from a high altitude is rejected. Illustration from Ruck, Aschehough et al. (2000).

3.3.4 The Retrolux system

The Retrolux system is made of fixed or tiltable blind slats with a special geometric construction that allows for both daylight redirection as well as solar shading. The system is developed and described by Köster (2004).

In a fixed configuration, the geometry of the slats makes it possible for the system to admit low elevation light but reject light from higher elevations, including light from the summer sun. For high latitudes overheating protection can also be required from low elevation sunlight. In such cases the tiltable configuration of the Retrolux system is more appropriate.

As indicated in Figure 3-8, the system also allows for viewing in the horizontal direction between the blind slats. As shown in the figure, the geometric construction includes a W-shaped form that reflects parts of the incoming sunlight back towards the exterior, preferably in a single reflection to reduce the absorption at the slat surfaces. Retrolux systems include exterior systems, interior systems and systems located between the panes of double-paned windows.

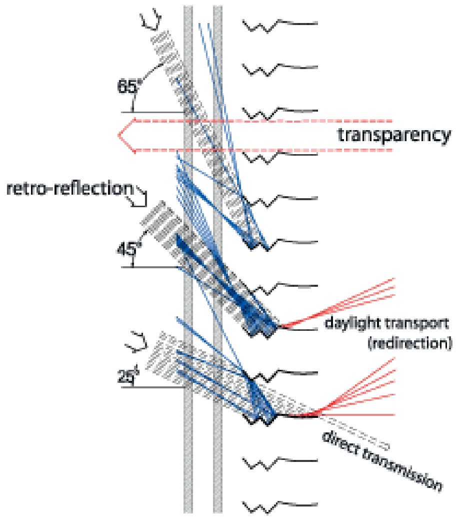


Figure 3-8 An example of a Retrolux system. The system consists of equally spaced reflective blind slats in a fixed position. In this illustration daylight is incident from the left. Due to the geometry of the slats, light from the high elevation summer sun is rejected, thus providing solar shading. The system allows for outward viewing in the horizontal direction between the slats. Illustration reprinted from Köster (2004).

3.3.5 The Retroflex system

The Retroflex system is also developed by Köster, and can be regarded as a modification of the Retrolux system. The Retroflex system is made of fixed or tiltable blind slats designed primarily for overheating protection. The blind slats are made of highly reflective aluminium and have a concave curvature and a surface that incorporates a saw tooth microstructure that acts as a retro-reflector for incoming sunlight. On the lower side, the slats are covered with a white, highly reflective matt paint. Due to the saw tooth microstructure, the system provides adequate overheating protection while also allowing for outward viewing between the blind slats.

As illustrated in Figure 3-9, the microstructure allows the blind slats to have a much lower tilt angle, while still rejecting the same amount of incoming light as that of highly tilted blind slats composed of an unstructured material. Since the light absorption is small, this type of microstructure is particularly useful when the blinds are located on the interior side of the glazing unit, or between the panes of a double glazing unit.

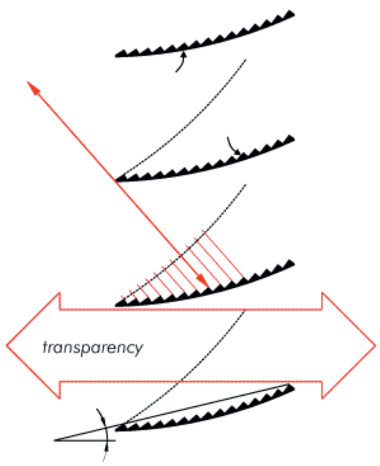


Figure 3-9 Illustration of the Retroflex system. The blinds incorporate a saw tooth microstructure that allows the system to reject incoming sunlight (from the left) while still providing a view out between the blind slats. Illustration reprinted from Köster (2004).

3.3.6 A louver system with refractive rods

A novel louver system with refractive rods has been developed and tested at the Building Technology Group of MIT (Thuot and Andersen 2011). The system consists of a vertical array of reflective louvers that redirect incoming light deep into the space and towards the ceiling of the interiors. The louvers change the elevation of the incoming light but they do not significantly alter the light's azimuth angle. In order to achieve this, the system also includes a row of vertically oriented refractive rods.

Figure 3-10 shows the layout and daylighting components of the system, incorporated in a double glazing unit.

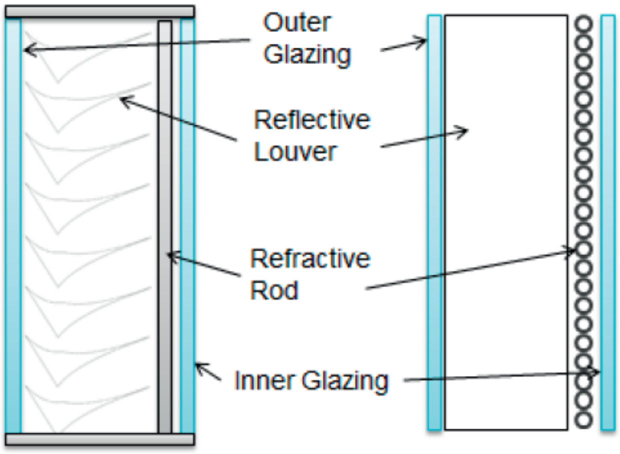


Figure 3-10 Illustration of the louver system with refractive rods. Side view (right) and top view (left). Illustration reprinted from Thuot (2011).

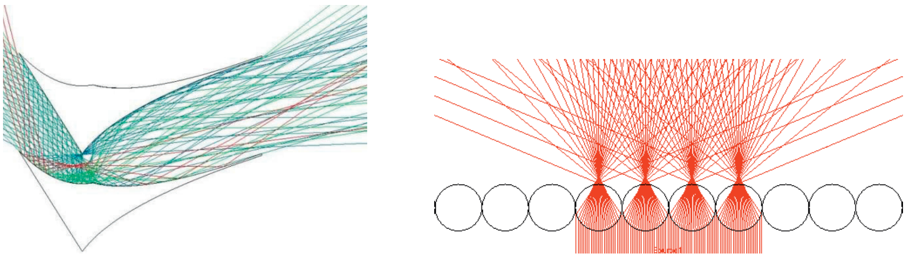


Figure 3-11 Illustration of ray tracing results. Side view of ray tracing through the louvers for different elevation angles (right). Top view of ray tracing through the transparent rods, illustrating the ability of the system to alter the azimuth angle of incident light (left). Illustrations reprinted from Thuot (2011).

3.4 Light shelves

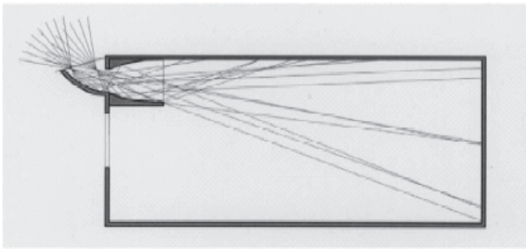
Light shelves can be used both to shade the building occupants from direct sunlight and also to redirect daylight for improved light distribution within the interiors. According to Ruck, Aschehough et al. (2000), a light shelf is a truly classic daylighting system that was known as far back as in the days of the Egyptian Pharaohs.

The conventional light shelf is a horizontal panel of an opaque material that is positioned inside and/or outside of the window facade. Light shelves are normally positioned above eye level, dividing the window into a view area below the shelf, and a clerestory area above. The conventional light shelf is considered to be most effective in direct sunlight, providing shading, glare protection and redirection of sunlight.

More sophisticated light shelves can be composed of semi-transparent materials or materials with other specially designed optical characteristics. It is also common to tilt the light shelf upward or downward to adjust the performance of the shelf, see Figure 3-12 (a). Also, the shape of the shelf can be designed to increase performance with respect to daylight redirection. An example of a specially designed shape is the anidolic zenithal collector discussed by Scartezzini (2002) and shown in Figure 3-12 (b). The term anidolic refers to non-imaging optics (an: without, eidolon: image). According to Scartezzini, anidolic systems were developed following the principles of non-imaging optics and take advantage of these principles to achieve outstanding performance with respect to daylight collection and re-distribution.

As mentioned above, it is possible to tilt the light shelf to adjust the performance. The effect of this is illustrated in Figure 3-13. An upward tilt will increase the daylight penetration, but reduce shading. A downward tilt will increase shading, but reduce daylight penetration. According to Ruck, Aschehough et al. (2000), a horizontal light shelf usually provides the best compromise between shading requirements and daylight distribution.

(a)



(b)

Figure 3-12 Two examples of innovative light shelves. (a) Semi-transparent double light shelves made of reflective glass. Picture from Ruck, Aschehough et al. (2000). (b) An anidolic zenithal collector. The illustration indicates the path of light rays from diffuse daylight through the system. Illustration from Scartezzini (2002).

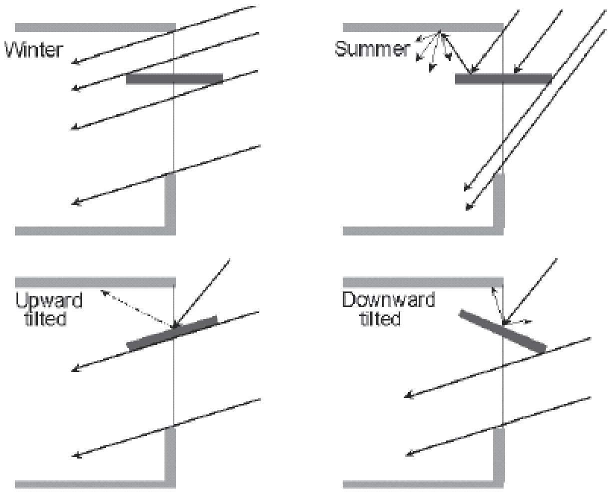


Figure 3-13 An example of a partly exterior and partly interior light shelf with a specular upper surface. The upper illustrations show the paths of sunlight when the light shelf is in the horizontal position. The lower illustrations show the effect of an upward or downward tilting. An upward tilt will increase the daylight penetration, while a downward tilt will increase the shading effect. Illustration from Ruck, Aschehough et al. (2000).

3.5 Prismatic elements

Prismatic elements are made of a transparent material, usually polymer, and shaped as planar elements with a flat surface on one side and a patterned prismatic structure on the other side. According to Baker (2002), prismatic elements are available either as panels about 10 mm thick, or as thin flexible films less than 1 mm thick. Prismatic elements are often integrated in a double glazed unit to assure low maintenance. Prismatic elements operate on the two optical principles of refraction and total internal reflection. Several geometries of the prismatic structure are available, designed for different applications. The original function of the prismatic element was to redirect diffuse light from the zenith region of the sky towards the back of a heavily obstructed room. An early version of this type of prismatic element was called Luxfer-prisms, and these were applied in Berlin as early as 1902 (Baker, Fanchiotti et al. 1993). Prismatic elements can also be designed to reflect light from certain angles while transmitting light from other angles. This type of prismatic element can be used as a sun-shading device. The current main applications of prismatic elements are for:

- sun-shading
  - fixed sun-shading system
  - moveable sun-shading system
- daylight redirection
  - diffuse daylight redirection system
  - sunlight redirection system

The various applications are described by Ruck, Aschehough et al. (2000). Fixed sun shading systems are designed to reject direct sunlight, but transmit and redirect diffuse daylight. In this system, sunlight rejection is provided by a reflective aluminium coating on one of the surfaces of the prism, as shown to the left in Figure 3-14. According to Ruck, Aschehough et al. (2000), fixed sun-shading systems are normally found in glazed roofs. Moveable sun-shading systems reject sunlight that is incident from a certain direction by the mechanism of total internal reflection, as shown to the right in Figure 3-14. In moveable sun-shading systems the prismatic panels are normally provided as tiltable louvers.

Daylight redirection is also an important function of the prismatic element. For this means the panels can be positioned in the vertical window plane to redirect daylight deeper into the interiors, typically via the ceiling, as illustrated in Figure 3-15. In principle, such panels reduce the luminance of the windows, and therefore function as an anti-glare system (Ruck, Aschehough et al. 2000). However, according to Baker (2002), unwanted downward light beams are often produced at the same time, and these may cause glare problems in direct sunlight conditions.

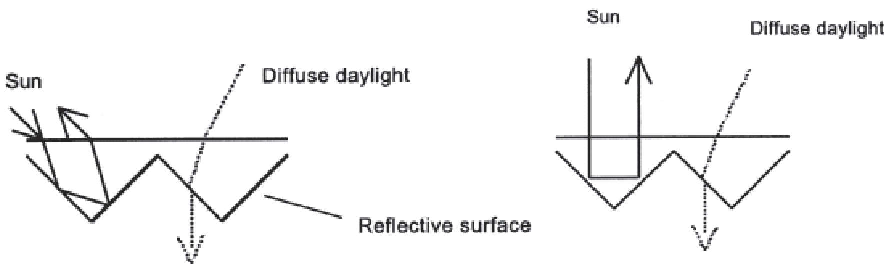


Figure 3-14 Prismatic elements as sun-shading devices. Left: Fixed sun-shading systems reflect incident sunlight from certain relevant directions by a reflective coating on one of the prism surfaces. Right: Moveable sun-shading system reflects sunlight incident from a certain direction by the mechanism of total internal reflection. Illustration from Ruck, Aschehough et al. (2000).

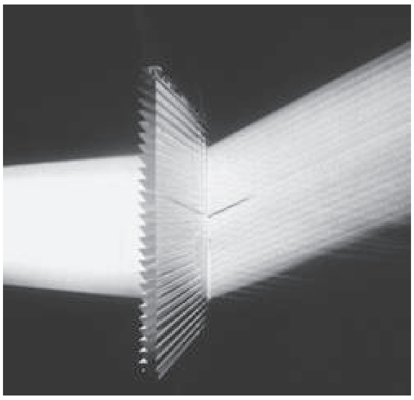


Figure 3-15 An illustration of light redirection by refraction in a prismatic panel. Light incident from the left is redirected upwards. Picture reprinted from Ruck, Aschehough et al. (2000).

Prismatic elements are translucent and distort the view to the outside. When such elements are positioned vertically in a window opening it is therefore preferable to install the panels in the upper part of the façade opening, above a view window.

The light transmittance through a prismatic element can be quite high, depending strongly on the direction of incident light. It is typically about 90% for the transmitting directions (Herrmann, Rosemann et al. 1999). For diffuse light the transmittance is much lower due to total internal reflections inside the panel. Based on the optical properties, prismatic elements can be quite effective in redirecting sunlight with low light losses, but are less effective under diffuse light conditions.

Despite this, several studies have shown that in overcast conditions, prismatic elements decrease daylight factors slightly compared to a similar room with clear glazing (Ruck, Aschehough et al. 2000). Based on this it has been concluded that prismatic elements have limited applications in climates dominated by overcast sky conditions.

Nevertheless, simulation studies have also shown that in highly obstructed locations, prismatic systems can redirect skylight deeper into the room and therefore significantly improve daylight factors (Baker and Steemers 2002).

3.6 Laser cut panels

The name laser cut panel (LCP) refers to a method that has been used in the production of an innovative light deflection system. The original LCP system was developed by Edmonds (1993) and is also known as Edmonds panel. Later, light deflection systems based on the same optical principles but produced by different methods have been developed; by moulding and lamination (Serraglaze) and by extrusion (Inglas).

According to the inventor, laser cut panels can be mounted as the primary glazing or as a second internal glazing in the upper part of a window to perform the same function as a light shelf or reflective blind system. The original Edmonds panel is produced by making parallel laser cuts to produce voids in a clear acrylic material (Edmonds 1993). The surface of each laser cut deflects light passing through the panel by the mechanism of total internal reflection (as discussed in section 3.2.3).

Light that passes through the panel is deflected at each interface by a sequential process of refraction, reflection and refraction. The principle of operation is illustrated in Figure 3-16. In this illustration an important performance characteristic of the LCP is given; the fraction of light deflected as a function of incidence angle. From the figure it is evident that a vertical LCP strongly redirects light incident from higher elevation angles (>30°) to the upward direction, while transmitting light at near normal incidence with little disturbance, thus maintaining view in this direction. Also shown in the figure is how the fraction of deflected light depends on the ratio between the cut spacing distance (D) and the distance that the cut extends through the panel (W).

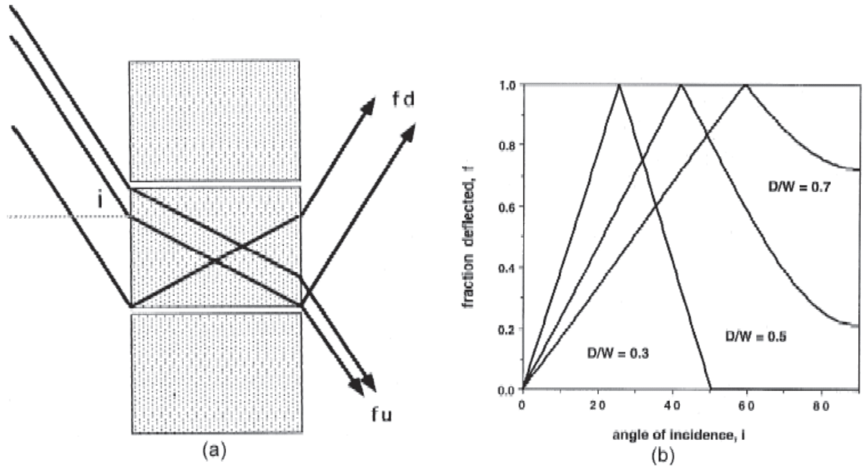


Figure 3-16 (a) The principle of operation for a laser cut panel. The sequential refraction, total internal reflection and refraction at the interfaces produce a deflected fraction (fd) with the remaining fraction (fu) transmitted without deflection. (b) The fraction of light deflected as a function of incidence angle for LCP with cut ratios D/W of 0.3, 0.5 and 0.7 respectively. The effect of first-surface reflection is not included in these results. Illustrations from Edmonds (2002).

The principle of operation including the mechanism of total internal reflection assures that very little light is absorbed in the LCP. However, due to surface reflections, the amount of light that is transmitted through an LCP is comparable to that of an acrylic plate, about 92% for normal incidence and less for oblique angles of incidence.

Laser cut panels have been tested at high latitudes by Arnesen (2002). Full-scale tests with LCP installed in the upper part of a vertical window showed that they have very little effect on the daylight factor. For clear sky conditions however, the LCP increases the illuminance levels significantly in the intermediate and rear zones of the test room, as compared to a reference room with an unobstructed window. The laser cut panel also provides more light in the space than a conventional venetian blind system with white blinds.

Laser cut panels can also be applied in a window blind configuration. The illustration in Figure 3-17 shows laser cut panels applied as blinds between the window panes in a double glazing unit. One important benefit of this system is that solar shading by rejection of high elevation sun radiation can be combined with a relatively good view to the outside in the horizontal direction.

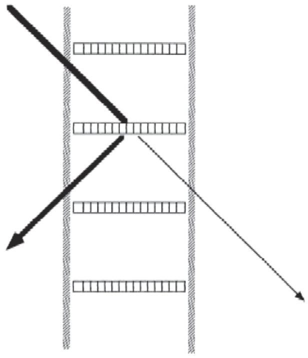


Figure 3-17 Laser cut panels applied as blinds between the panes in a double glazing unit. The thick line illustrates sunlight that is incident from the left. Most of the incident sunlight is rejected and the system thus provides solar shading. A partial view is provided in the horizontal (and near-horizontal) direction between the blind slats. Illustration from Edmonds (2002).

3.7 Sun-directing glass

The sun directing glass was previously available from the (former) company LIFLITE GmbH. The main component of sun-directing glass is a stack of curved acrylic elements that are positioned between two panes of glass, comprising a sealed glazing unit. The acrylic elements function as optical light guides on the principle of total internal reflection.

The acrylic elements effectively redirect downward directed incoming light from angles in the operating region of 15° - 65° towards the upward direction (ceiling). The principle of operation is illustrated in Figure 3-18. In addition to this vertical redirection (altering the elevation angle), the sun-directing glass also redirects incoming light horizontally (altering the azimuth angle), to provide a more even horizontal distribution. This is achieved by corrugating the trailing end of the acrylic elements; see section (4) in Figure 3-18.

The sun-directing glass is designed primarily for redirecting sunlight. Diffuse will also be transmitted and redirected, but the loss of light is in this case a significant drawback. Product information supplied by LIFLITE indicates that a double glazing unit of sun-directing glass transmits about 50% of the visible daylight, whereas a conventional double glazing transmits about 80%. According to a test carried out at the Technical University of Berlin, the sun-directing glass decreases the interior illuminance levels compared to conventional glazing under overcast sky conditions (Ruck, Aschehough et al. 2000).

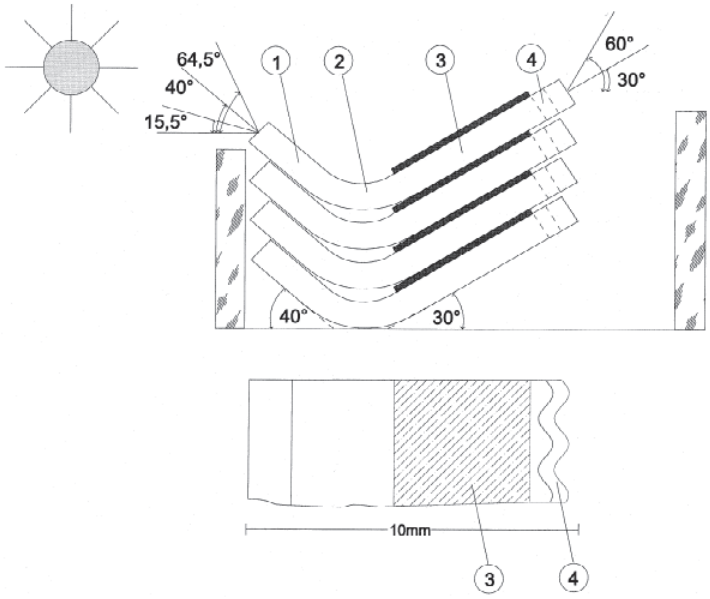


Figure 3-18 Schematic illustrations of sun-directing glass. The two illustrations show the same element as seen from the side and from above respectively: Incident light impinges onto the straight leading section (1) which is inclined at an angle of 40° from the horizontal. A curved middle section (2) redirects incident light via total internal reflection. The straight end section (3) is tilted 30° from the horizontal for illumination without glare. At its trailing edge, the end section is fitted with a corrugated strip (4), which scatters the light in the horizontal plane and also serves to redirect obliquely impinging light towards the centre of the room. Illustration and text from Beck et al. (1999).

The sun-directing glass is translucent, and does not provide a view to the outside. The system is normally positioned in the window area above eye height in order to avoid glare and to allow for an undisturbed view through the lower part of the window opening. The sun-directing glass can also be placed in front of the window façade, or behind it in retrofit situations (Ruck, Aschehough et al. 2000).

The combination of vertical and horizontal redirection of sunlight results in a relatively uniform illumination of the ceiling. The illumination is to some extent independent of the position of the sun, as indicated in Figure 3-19. It is significant that this uniform distribution is achieved without any moving parts. Because of the uniform distribution of redirected sunlight in the ceiling it is unlikely that the ceiling will cause glare. However, according to Ruck, Aschehough et al. (2000), it is possible that the bright luminance of the sun-directing glass itself may be a source of discomfort glare. The luminance values with sun-directing glass have been measured and compared to values with conventional glazing (Beck, Körner et al. 1999). For upward viewing directions (above 15° from the horizontal plane) luminances are reduced significantly, but according to Beck et al. (1999), a glare-free illumination of offices with workstations cannot be guaranteed. However, the sun directing element can be equipped with an optimised coating on the end section in order to reduce the potential glare problem.

Figure 3-19 Illustration of light distribution in a sidelighted space without (left) and with (right) sun-directing glass in the clerestory portion of the window opening. Pictures reprinted from the (former) website of the company LIFLITE GmbH.

3.8 Switchable windows

New technological solutions allow for glazing units with variable optical transmittance properties, achieved without moving parts. The transmittance can either be controlled by an electric impulse, or it can adapt to physical conditions such as e.g. light intensity or temperature. These advanced glazing solutions are commonly referred to as smart or switchable windows. More specifically, depending on the technology used, the systems are referred to as electrochromic, gasochromic, photoelectrochromic or photochromic glazing. A review article about switchable windows is provided by Baetens et al. (2010). One of the most promising technologies for switchable windows is electrochromic windows based on tungsten oxide (WO_3). A good overview of the different types of switchable windows, with a focus on systems based on tungsten oxide is given by Georg et al. (2008). Windows based on tungsten oxide have to states. The transmittance is high in the so-called bleached state and low in the coloured state. In Table 3-1 the typical transmittance values in bleached and coloured state for different switchable windows systems based on tungsten oxide is given, as presented by Georg et al. (2008). Both values for visible light transmittance (τ_{vis}) and for solar energy transmittance (τ_{sol}) are given.

Table 3-1 Typical transmittance values in bleached and coloured state for different switchable windows systems based on tungsten oxide.

Type of switchable glazing	τ_{vis} bleached [%]	τ_{sol} bleached [%]	τ_{vis} coloured [%]	τ_{sol} coloured [%]
Gasochromic double glazing	77	76	6	5
Electrochromic glazing	63	46	1.2	0.7
Photoelectrochromic glazing	62	41	1.6	0.8
Photochromic glazing	60	40	6	2

The results show that solar energy transmittance can be reduced to very low levels with switchable window technology. In this respect switchable windows can be compared to other more conventional shading devises.

The results in Table 3-1 show that the gasochromic switchable glazing provides the highest light transmittance in the bleached state. Note that the values for the gasochromic technology are given in a double glazing configuration whereas the other values presented are for a single glazing. High light transmittance can be regarded as an advantage in situations with low daylight supply, such as e.g. under overcast skies. On the other hand, the values for light transmittance and solar energy transmittance for the gasochromic glazing are also higher in the coloured state. As will be discussed below, this can be a negative factor with respect to the potential for glare protection.

The visual performance of switchable windows is quite different from most other types of shading systems. The visual quality assessment of switchable windows was discussed by Moeck et al. (1996). As noted by Moeck, the visual performance of switchable windows has not been explored extensively. Since the materials were not available in large sizes for full-scale occupant studies, Moeck used the computer visualisation program Radiance to draw some conclusions about the visual performance. One of the conclusions from Moeck's study was that a low visible transmittance in the order of 1% was needed to provide adequate glare protection under direct sunlight conditions. This applies for an office environment where the window luminance is to be kept below 850 cd/m^2. However, as concluded by Moeck, such very low light transmittance values will require the use of interior electric lighting and significantly reduce energy efficiencies since daylight will be largely eliminated from the room. "Furthermore, many office occupants may not accept such a low transmission glazing, since exterior view quality and connection to the outdoors will be diminished for those hours when there is direct sun or high exterior illuminance levels. Alternative fenestration designs with shading systems or other design strategies that split the exterior wall into a higher placed daylight admitting element and a lower, controlled transmission view window, may provide a more acceptable solution".

It is clear that switchable windows have many advantages compared to conventional glazing. However, the need for improved daylight distribution is not addressed by altering the transmittance properties. Therefore, as indicated by Moeck, a combination of switchable windows together with more conventional solar shading and daylight redirection systems could be a promising solution.

3.9 Performance metrics for assessment of daylighting systems

In the previous sections several systems for daylight redirection and solar shading were discussed. In this section the main focus is on the performance metrics used for assessing the performance of such systems. Several studies have been carried out with the aim to evaluate the performance of various different systems. Some of the studies have focused on the daylighting performance of the systems, e.g. (Aizlewood 1993), (Littlefair, Aizlewood et al. 1994), (Moeck 1998) and (Arnesen 2002). Other studies have focused on the shading performance of the systems, e.g. (Wall and Bülow-Hübe 2001), (Wall and Bülow-Hübe 2003) and (Rosencrantz 2005). Finally, only a limited number of studies have looked at the performance with respect to potential for viewing (Dave and Andersen 2012).

A range of different methods have been applied in the studies. Some of the studies have relied mainly on physical measurements, other studies have focused on user responses and some studies are based mainly on computer simulations. Also, the criteria for evaluating the performance have varied. Some of the studies have limited their investigation to only one or two quantifiable system attributes, while other studies have tried to evaluate several aspects of the systems. In the following, a few of these studies will be discussed and a particular emphasis will be put on the criteria that are used to evaluate system performance.

A study by Aizlewood (1993) compared several innovative daylighting systems to clear conventional glazing. This study was based on full-scale physical testing in mock offices. The systems tested included lightshelves, various prismatic systems, as well as the Okasolar system (see section 3.3.3). The innovative daylighting systems were positioned on the upper half of the window opening in deep, sidelighted mock offices.

Two performance criteria were used in this study. The first criterion was the increase in workplane illuminance using the innovative system compared to a conventional glazing. This measure was used to provide information about the daylight supply provided by the system. The results from the study show that most of the systems decrease the illuminance at the back of the test room. This is also the case under cloudy conditions when the need for supplementary electric lighting is generally the greatest. However, the author concludes that the comparison with a conventional glazing is not completely fair. “In practice, most offices are shaded with blinds. These reduce direct solar heating in summer and act as glare control device all year. The innovative systems could displace such blinds provided that they limit window glare to an acceptable level. A fairer comparison might be, therefore, between the innovative systems and the shading and light redistribution properties of venetian blinds, assuming typical levels of blind use: a comparison in which the innovative systems would look far more favourable”.

The second criterion used in this study was the *daylight glare index* (see section 2.4.2). This measure was used to evaluate the various systems effect on window glare. The results show that all of the systems tested reduce the window glare. Conditions that were “uncomfortable” without any shading device typically became “acceptable” with the shading device present, according to the daylight glare index. However, as noted by the author, some caution should be expressed in the interpretation of these findings. “Firstly, the study period relates to autumn and spring performance. There are no data for glare control in summer or winter. Secondly, it is likely that the lower, conventionally glazed, part of the window would require blinds to protect the occupants near the window from direct low-angle sunlight. This would affect window glare. Thirdly, these measurements treat the innovative systems as extended glare sources. Each system could on occasion produce extremely bright points or lines, in direct sunlight. These then acts as point glare sources and could cause discomfort. This is not covered by the DGI system, which only considers glare from the sky, not direct sunlight.”

The study by Aizlewood was based entirely on measurements. Yet, the author concludes that computer simulations have the potential to predict the impact of innovative glazing. According to the author, such simulations can be used to assess a wider range of glazing system parameters such as the effects of prismatic glazing angles or light shelf geometry. It can also be used to extend the findings to more arbitrary room geometries.

The conclusions from Aizlewood can be regarded as the starting point of a study by Moeck (1998). The author here proposed a set of performance criteria addressing both daylight quantity and quality for advanced daylighting systems. Further, the performance according to the proposed criteria is simulated using the ray tracing program Radiance.

In Moeck’s study, six different daylighting systems for a vertical south-facing facade were compared, including a white venetian blind system as a reference case. The various other systems that are compared to the reference case include standard clear glass, various prismatic systems and an innovative blind system similar to the Okasolar system presented in section 3.3.3. Some of the systems considered were stationary and some were sun-tracking.

The following eight performance criteria were proposed and used by Moeck: a) luminous intensity distribution of the system for a specific time, b) illuminance on the workplane, c) illuminance distribution on the workplane, d) total lumens entering the space, e) total lumens in the upper back zone of the space, f) luminance of the window, g) total area in space that is overbright and h) spherical illuminance values.

This set of criteria was proposed by the author as a first basis for a rating system for daylighting systems in office buildings, but not for view windows. According to the author, the view to the outside is not considered due to the difficulty of separating the effects of the view window from the daylight system. Apparently, the author implies that it is difficult to evaluate the need for a view through the daylight opening when a view window is also present.

The author assumed that the reference system with white venetian blinds is controlled to exclude direct sunlight. Therefore, the venetian blind system is sun-tracking for sunny skies, and positioned with horizontal (untilted) slats for overcast skies. According to the proposed criteria and simulations, the white venetian blind system performs poorly with respect to daylight levels. Nearly all of the other systems studied admitted more light into the room, besides performing better in other areas too. Even on overcast days when the blind slats are not tilted, two of the other systems (the Okasolar system and one of the prismatic systems) perform significantly better than the white blinds. However, the author also notes that the performance of the venetian blind system could be improved. For example, performance with respect to redirecting more light towards the rear ceiling could be increased by choosing specular metal instead of white glossy paint. Also, more sophisticated control strategies for the venetian blinds could be considered. The author proposes an alternative strategy that holds the illuminance of the blinds within a defined range at all times. With this strategy the blinds might even become superfluous under certain low luminance sky conditions. In principle, under such conditions, blinds could therefore be completely raised. In this case the daylight admittance of the system equals that of the clear glass and thus becomes significantly higher than for any of the stationary systems.

The study by Arnesen (2002) reported results from the testing of several daylighting and shading systems in full scale offices. The systems tested include interior light shelves, exterior light shelves, exterior venetian blinds, prismatic sun shading panels, laser-cut panels and Serraglaze panels. The main criterion used for the evaluation of the different systems was the daylight factor in the working plane. Of the tested systems, it was concluded that the laser-cut panel gives the best daylight uniformity in the working area. The author also commented briefly about the view through some of the systems. As noted by the author, some of the permanently fixed systems reduce the possibility for visual contact with the outside through the window. Based on a qualitative evaluation of the view it is concluded that the Serraglaze panels is the fixed system that provide the best view out through the window.

The studies by Wall and Bülow-Hübe (2001) and (2003) focused on the performance of solar shading devises. The first study focused on exterior shading devises and the second part also on interpane and interior devises. The results included measurements of the performance of a large selection of devises including awnings, exterior venetian blinds, fabric screens, roller shutters and solar control films. The performance criterion used in this study was the total energy transmittance values (g-values) of the shading device, the window and the combined system respectively. In addition to the measurements, the work also included the development of detailed calculation models for predicting g-values.

Results were reported from outdoor measurements in Lund (Sweden). The average g-value for each group of measured shading devices was 0.3 for exteriorly located products, 0.5 for in-between pane products and 0.6 for interior products. Thus, on average, exterior products performed much better than the interior products with respect to reducing peak cooling loads. Also in this study, the effect of the shading systems on the outside view was only briefly addressed with the following interesting statement: “In selecting shading products one should also pay attention to the transmitted daylight and the effect on the view out. The internal products yielding low g-values admit almost no daylight into the room, and totally obstruct the view out, two of the main reasons for having a window”.

Only a very limited number of studies have focused on the viewing potential through a daylighting or solar shading system. A recent performance metric, the *View Through Potential*, was defined by Dave and Andersen (2011). The view through potential is a measure of the fraction of incident light that is transmitted across a facade directly, with no distortion or diffusion. Values are calculated for a set of view locations in the interiors as well as a set of viewing directions on the facade. The set of locations and corresponding viewing orientations are given by dividing both the interior space and the facade opening into grids, as illustrated in Figure 3-20. The values for the different grid points are combined into a single value for View Through Potential (VTP) that weighs view angles according to their probability of occurring.

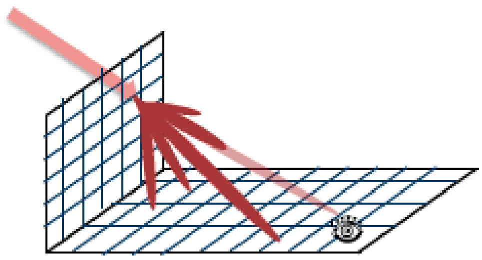


Figure 3-20 A schematic illustration of the *View Through Potential*. Illustration reprinted from Dave and Andersen (2012).

The validity of the new metric was investigated in a study of one hundred participants that were asked to view physical facade samples and rate them according to the possibility to see through them. The participants were informed that the samples were window materials and that they could view the samples at any angle to get an “overall view”. The results from this study summarised in Figure 3-21. According to Dave and Andersen (2012) the results from the user study confirm that the definition of the VTP is acceptable as a quantitative representation of view.

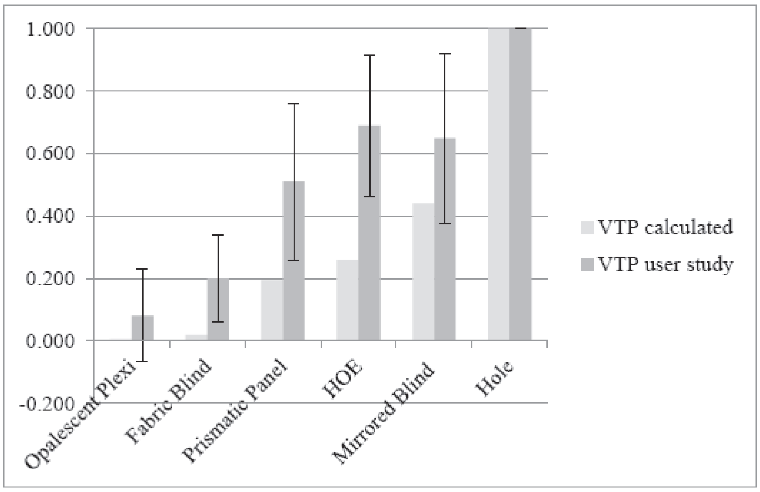


Figure 3-21 Comparison between calculated VTP and the subjective VTP as given by the participants in the user study. Illustration from Dave and Andersen (2012).

3.10 Summary and conclusions

Windows are not always desired; at times windows are also associated with thermal and visual liabilities such as solar heat gain, heat loss, and glare. Several types of shading systems are applied to address these negative aspects. However, it is a major challenge to control the negative aspects without also removing the positive attributes of windows.

Daylight redirection systems are designed not only to avoid glare, but also to utilise the available daylight in a good manner, and particularly the direct sunlight. Several different systems are available on the market today. Some systems have the ability to reduce overheating, while maintaining at least a limited outward view. Other systems are aimed primarily at preventing glare, and may totally eliminate the view out through the fenestration system.

However, for a daylighting system to perform well it needs to address several, often conflicting occupant needs and it should also function well under a number of different daylighting conditions. Establishing agreed upon performance criteria for such systems has therefore been a continued process.

It is noteworthy that a lot of effort has been put into assessing daylight performance of a particular (given) space, as shown in the previous chapter. The findings reported in this chapter suggest that much less effort has been addressed towards methods for assessing the performance of the daylighting system itself; the system that plays a major role in providing the daylight to the interiors of a building.

The findings also suggests that there is a need for new evaluation methods that address several aspects of the function of the system itself, independently from other factors such as the size and location of the facade openings, the orientation of the facade and the geometry of the space in which it is applied.

4 Fundamentals of venetian blinds

Everything one invents is true, you may be perfectly sure of that.
Poetry is as precise as geometry.

Gustave Flaubert

4.1 Introduction

In this chapter some of the fundamental principles related to horizontal venetian blinds are discussed. The discussion is directed towards blinds for daylight redirection, but is applicable also for traditional venetian blinds located in view openings. The results in this chapter depend mainly on geometrical considerations, and no simulation results are presented here. The coordinate system used to define the position of the sun is introduced (section 4.2), as well as the geometric parameters needed to define horizontal slat-type blinds (section 4.3). In section 4.4 the blind tilt required to eliminate direct sunlight is discussed, and section 4.5 discusses the concept of projected solar elevation. The direction of specularly reflected sunlight is of special importance for daylight redirecting blinds, and this subject is discussed in section 4.6. The ability to provide outward viewing between the blind slats is of importance for all blind types. A new way to illustrate the viewing potential in different viewing directions is introduced in section 4.7.

4.2 Coordinate system for the sky

For the discussion of blind geometry it is convenient to start with the position of the sun. Figure 4-1 gives the angles that will be used to define the position of the sun and arbitrary sky elements. The position of the sun is given by the sun's elevation angle (γ_s) and azimuth angle (α_s). The position of a sky element is given by the elevation angle (γ) and the azimuth angle (α).

In addition, the angle between the sky element and the sun (χ) is also shown, as well as the angle between a sky element and zenith (Z).

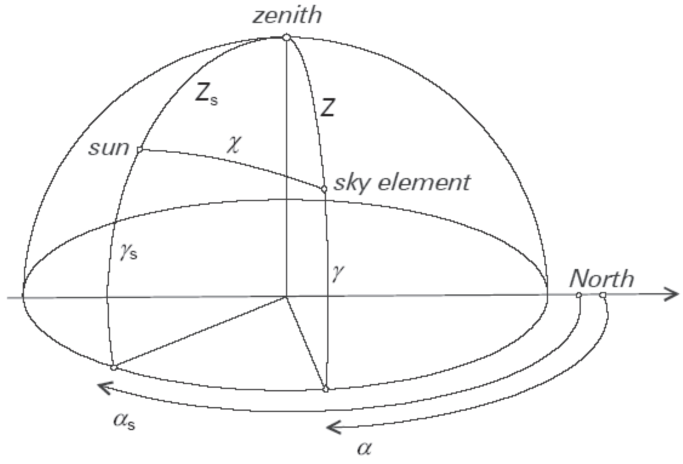


Figure 4-1 Angles defining the position of the sun and a sky element. Illustration reprinted from the ISO 15469:2004 *Spatial Distribution of Daylight – CIE Standard General Sky.*

4.3 Geometric parameters for horizontal blinds

It has been shown that the geometry of venetian blinds can have a very strong influence on the performance of the blind (Parmelee and Aubele 1952). In Figure 4-2 the most important geometric parameters of the horizontal venetian blind are defined: *W* is the width of the blind slats, and *S* is the spacing between adjacent slats. The relation between these two, the spacing to width ratio (*S/W*) is an important parameter. The thickness of each blind slat is given by *t*. For simulation purposes, the thickness is often negligible compared to the width and spacing. In practice, the blinds are often curved, and the radius of curvature is given by r_c. Typically, the blinds are oriented with the concave side of the slats pointing towards the ground, as shown in Figure 4-2. However, blinds optimised for daylight redirection are typically oriented with the concave side pointing upwards. The blind tilt is given by the angle β. It is positive when the blinds are tilted down towards the exterior ground, as shown in Figure 4-2.

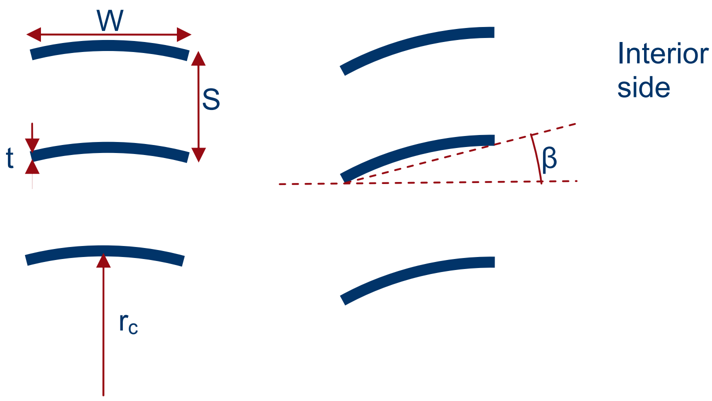


Figure 4-2 Parameters used to define the geometry of horizontal venetian blinds.

In the following sections four different spacing to width ratios (*S/W*) are discussed in order to illustrate the importance of this parameter. The different spacing to width ratios corresponds to different overlap between two adjacent blind slats. The fraction of a slat that is overlapped by the adjacent slat (*O*) when the blinds are fully closed is given by the simple relation below.

$$O = 1 - \frac{S}{W} \tag{4.1}$$

Table 4-1 Overlap between adjacent blind slats for different *S/W*.

S/W	0.6	0.7	0.8	0.9
Overlap	40%	30%	20%	10%

It should be noted that this is the overlap between two adjacent blind slats. In a typical venetian blind configuration with multiple slats, the indicated overlap will therefore occur at both ends of each slat (except for the upper and lower slat).

4.4 Blind tilt for sunlight cut-off

The blind slats can be tilted so as to avoid direct sunlight from entering into the interiors. Avoiding direct sunlight is often an absolute requirement to avoid problems with glare. The blind tilt for sunlight cut-off ($\beta_{cut\text{-}off}$) is here defined as the minimum tilt angle that assures that no direct sunlight can pass between the blind slats. This means that the sunlight cut-off tilt will be positive for low sun elevations and negative for high sun elevations. The cut-off tilt is important for several reasons, especially for daylight redirecting blinds located at elevated locations (above eye height) in the window facade. Firstly, tilting the blind slats to the cut-off angle (and not further) enhances the view towards the sky. Secondly, in many typical situations, tilting the blinds to the cut-off angle (and not further) assures that redirected sunlight is sent far back towards the deeper interiors of a space, where it is normally needed the most.

The blind tilt for sunlight cut-off is illustrated in the figure below.

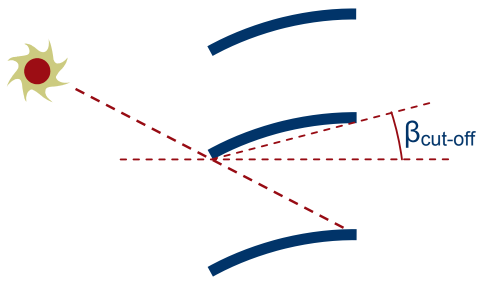


Figure 4-3 Illustration of the blind tilt for sunlight cut-off.

4.5 Projected solar elevation

It should be noted that the sunlight cut-off tilt depends on the position of the sun; both the solar elevation (γ_s) as well as the azimuth angle of the sun relative to that of the window normal (the azimuth difference angle, $\Delta\alpha_s$).

When the sun is not positioned in the normal plane of the window ($\Delta\alpha \neq 0$), it is convenient to project the sun position into a plane that is perpendicular to the window and find the solar elevation in this plane: the projected solar elevation (γ'_s). The projected solar elevation angle (γ'_s), lies in a plane that is perpendicular to the window ($\Delta\alpha = 0$). See illustration in Figure 4-4. The projected solar elevation angle (γ'_s) is always equal to or larger than the real solar elevation (γ_s).

The projected solar elevation has also been named the profile angle of the sun (Parmelee and Aubele 1952).

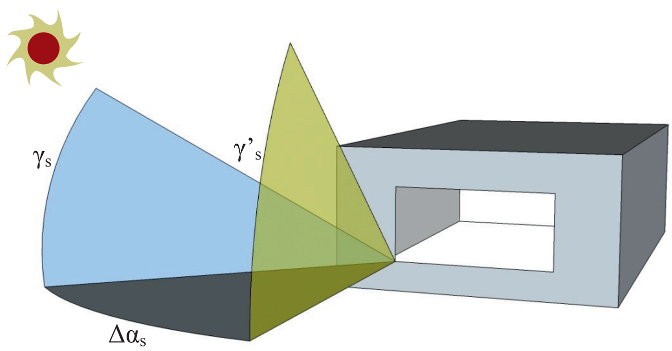


Figure 4-4 The sun position relative to the window normal is defined by the solar elevation (γ_s) and the azimuth (difference) angle relative to the window normal ($\Delta\alpha_s$). The projected solar elevation angle (γ'_s), lies in a plane (shown in yellow) that is perpendicular to the window ($\Delta\alpha = 0$).

For a solar position given by solar elevation (γ_s) and azimuth angle ($\Delta\alpha_s$), the projected solar elevation is given by:

$$\gamma'_s(\gamma_s, \Delta\alpha_s) = \arctan\left(\frac{\tan\gamma_s}{\cos\Delta\alpha_s}\right) \quad (4.2)$$

Parmelee and Aubele (1952) discussed the implications of this equation and presented a figure showing the projected solar elevation (or profile angle of the sun) for different solar elevations and azimuth (difference) angles.

In later chapters, 10 different daylight scenes that are relevant for high latitudes will be studied; one scene to represent the overcast sky, three scenes to represent low sun conditions ($\gamma_s = 10^o$), three scenes to represent intermediate sun conditions ($\gamma_s = 30^o$) and three scenes to represent high sun conditions ($\gamma_s = 50^o$). Table 4-2 gives the projected solar elevation for the nine different daylight scenes with direct sunlight. It is clear that an increase in the azimuth angle results in a larger projected solar elevation angle.

Table 4-2 Projected solar elevation for different daylight scenes.

Scene	Solar elevation (γ_s)	Azimuth diff. angle ($\Delta\alpha_s$)	Projected solar elevation (γ'_s)
2	10º	15º	10.3º
3	10º	45º	14.0º
4	10º	75º	34.3º
5	30º	15º	30.9º
6	30º	45º	39.2º
7	30º	75º	65.9º
8	50º	15º	51.0º
9	50º	45º	59.3º
10	50º	75º	77.7º

Assuming that the blinds are flat ($r_c = \infty$) and the slat thickness is zero ($t = 0$), geometrical considerations can be used to find a relation between the cut-off tilt and the projected solar elevation:

$$\beta_{cut-off}(\gamma'_s) = \arcsin\left(\frac{S}{W}\cdot\cos\gamma'_s\right) - \gamma'_s \qquad (4.3)$$

Using the projected solar elevations given in Table 4-2, the above equation for cut-off tilt can be used to calculate the minimum blind tilt that is necessary for sunlight cut-off for each of the nine daylight scenes.

It is clear from equation 4.3 that the sunlight cut-off tilt depends on the spacing to width ratio, *S/W*. Figure 4-5 shows the blind tilt at sunlight cut-off for four different *S/W* ratios. Note that both positive and negative blind tilts are shown in this figure.

The sunlight cut-off tilts for the different clear sky scenes (S2 to S10) are given in Table 4-3. These values will be frequently used in the following chapters for determination of blind tilt in the TracePro models.

In some situations with high projected solar elevations, equation 4.3 will result in a negative blind tilt. In such situations it is a possibility to keep the blinds in the horizontal position ($\beta = 0$), to maximise the view out between the blind slats in the horizontal direction. From Figure 4-5 it can bee seen that untilted blinds with a spacing to width ratio of less than 0.9 will exclude direct sunlight as long as the projected solar elevation is more than 42 degrees. From Table 4-2 it can bee seen that this applies for daylight scenes 7 to10.

However, for daylight redirecting blinds it should be noted that keeping the blind slats untilted ($\beta = 0$) will affect the direction of redirected sunlight and might lead to less light redirected towards the deeper interiors.

As could be expected, the graphs in Figure 4-5 show that blinds with a high *S/W* needs to be more tilted to achieve sunlight cut-off. As will be shown in the following sections, this has an impact on the direction of reflected sunlight as well as on the viewing potential through the blind slats.

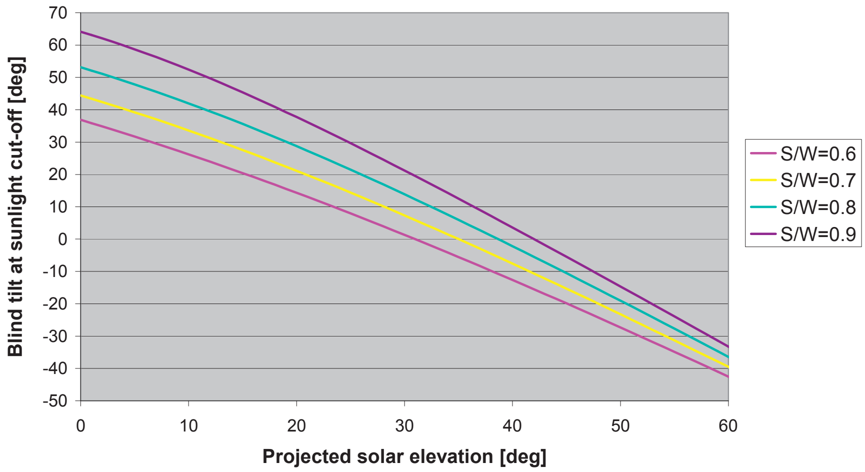


Figure 4-5 Blind tilt at sunlight cut-off for different spacing to width ratios.

Table 4-3 Blind tilt for sunlight cut-off for different spacing to width ratios.

Scene	Solar elevation (projected)	Blind tilt at sunlight cut-off			
		S/W = 0.6	S/W = 0.7	S/W = 0.8	S/W = 0.9
2	10.35°	25.83°	33.18°	41.56°	51.95°
3	14.00°	21.60°	28.78°	36.91°	46.84°
4	34.27°	-4.54°	1.08°	7.12°	13.79°
5	30.87°	0.13°	6.06°	12.50°	19.71°
6	39.23°	-11.54°	-6.40°	-0.94°	4.97°
7	65.85°	-51.65°	-49.21°	-46.75°	-44.25°
8	50.97°	-28.78°	-24.82°	-20.73°	-16.45°
9	59.32°	-41.49°	-38.39°	-35.22°	-31.98°
10	77.75°	-70.43°	-69.20°	-67.97°	-66.74°

4.6 Direction of specularly reflected sunlight

The blind tilt given in Figure 4-5 gives the minimum tilt required to provide sunlight cut-off. For blind slats with a specular upper surface aimed at redirecting direct sunlight far into the interiors (under a low angle with respect to the horizontal plane) this has a profound influence on the performance.

It is of interest to calculate the angle of the reflected light with respect to the horizontal plane. A sidelighted space as illustrated in Figure 4-6 is considered.

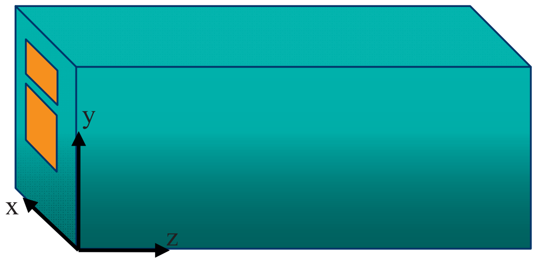


Figure 4-6 Illustration of a sidelighted space. The window facade lies in the xy-plane, and the yz-plane is perpendicular to the window.

For simplicity, also here all angles are projected into the plane that is perpendicular to the window (the yz-plane). Considering the simple case of flat blinds, the angle of the reflected sunlight above the horizontal (γ'_{int}) can be derived from the laws of specular reflection; giving the following equation:

$$\gamma'_{\text{int}}(\gamma'_s) = \gamma'_s + 2 \cdot \beta_{cut-off} \tag{4.4}$$

This result is illustrated for different *S/W* in Figure 4-8. Only angles of reflected light in the region from 0º to 90º (above the horizontal plane) are shown. Sunlight specularly reflected in a direction below the horizontal plane could cause glare. This is not difficult to avoid, as the blinds can be tilted slightly more upwards while still providing sunlight cut-off. From the graphs it is clear that when the projected solar elevation is higher than approximately 45º to 60º (depending on S/W ratio), the blinds should be tilted slightly above the cut-off angle to avoid downward specular reflections.

It should be noted here that for very high (projected) solar elevations extensive tilting of the blind slats might be required to avoid downward specular reflections. Under such conditions it could be a fundamental problem that the sunlight reflected from one slat is redirected towards the overlying slat. This shadowing effect could reduce the possibilities for efficient sunlight redirection towards the interiors of a space, as illustrated in Figure 4-7 (left).

For low sun conditions, the blinds need to be substantially tilted in order to block direct sunlight, and the angle (above the horizontal) of reflected sunlight is generally quite high. Sunlight reflected off a slat at 90º would be directed straight upwards, towards the overlying blind slat. But even when the sunlight is reflected at angles lower than 90º, a substantial part of the redirected sunlight might be blocked by the overlying slat, as illustrated in Figure 4-7 (right). This is more difficult to overcome, as tilting the blinds downward from the cut-off tilt angle could cause glare from direct sunlight entering between the blind slats.

The results given in the two previous equations are plotted in Figure 4-8. The results indicate that, for low solar elevations and as long as sunlight cut-off is needed, the blinds with the lower *S/W* perform better in redirecting sunlight at a lower angle. For example, for a projected solar elevation of 25º, the flat blind with *S/W* = 0.6 redirects sunlight in an angle of 41º above the horizontal while the flat blind with *S/W* = 0.9 redirects light at an angle of 84º, sending most of the light from one slat towards the overlying blind slat.

It should be noted that daylight redirecting blinds are often slightly curved, and this will modify the direction of the reflected sunlight. However, the graphs in Figure 4-8 provide a good indication as to why daylight redirecting blinds often have a relatively small spacing to width ratio compared to traditional blinds.

Yet, there are also potentially negative sides to a small *S/W*. Apart from the increased material consumption involved in the manufacturing of the blind; a small *S/W* will also have an impact on the viewing potential through the blinds. This is the subject of the next section.

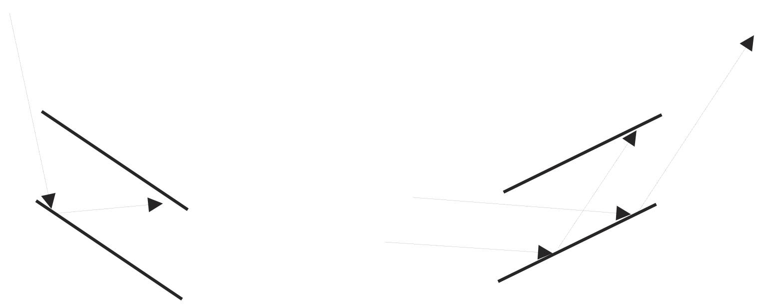


Figure 4-7: Illustration of venetian blinds operating under very high solar elevation (left) and very low solar elevation (right).

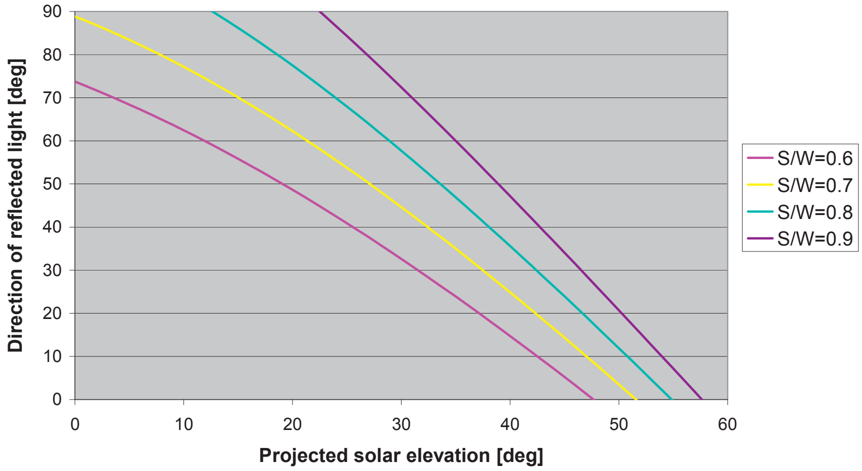


Figure 4-8 Angle (projected) of reflected sunlight from specularly reflective flat blind slats tilted to the sunlight cut-off position as a function of projected solar elevation. Note that the curves apply for a single slat. For multiple slat configurations it is more complicated since light reflected off from one slat could be blocked by the overlying slat.

4.7 Outward view

An important factor to consider is how the geometry and tilting of the blinds affects the view out.

A discussion of geometry and view was presented by Tzempelikos (2008). In his approach the effect of blind thickness and curvature was included. However, Tzempelikos only considered blinds with a spacing to width ratio (*S/W*) of 1, and he only considered the horizontal viewing direction. For daylight redirecting blinds smaller *S/W* are typically applied, and for blinds located above eye height upward viewing directions might be more relevant than the horizontal direction. Also, as noted by Tzempelikos, for thin slats the correction for thickness becomes negligible. Similarly, for slats with a very slight curvature the effect of the curvature on viewing is also negligible.

In the following a different approach is outlined. It is based on the calculation of the free view fraction (*f*), as discussed by Wirth and Gombert et al. (1998). The free view fraction is simply the fraction of the window area that allows for unobstructed view (between the blind slats) in a given direction.

It is here considered a venetian blind type fenestration system with slats of width W and a spacing distance S between the slats. Obstructions in view occur due to slat thickness, slat curvature and slat inclination. The *horizontal* free view fraction ($f_{0°}$) is determined by the fraction of the area that is open to unobstructed (free) view in the horizontal viewing direction. This is illustrated in the figure below.

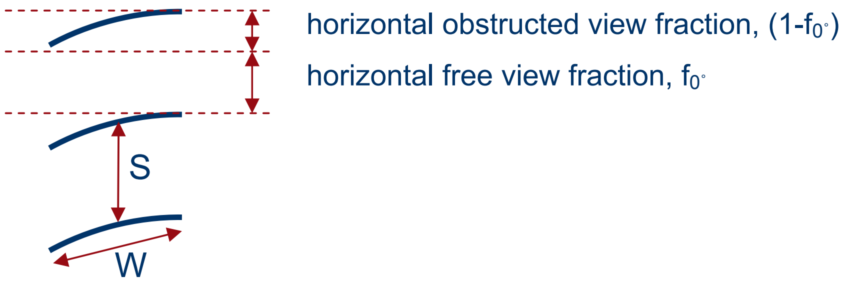


Figure 4-9 Illustration of horizontal free view fraction.

It is also of interest to calculate the free view fraction in directions lying above or below the horizontal, specified by the elevation angle γ. It is here considered most relevant to address directions (γ') lying in the vertical plane perpendicular to the window, as illustrated in Figure 4-10.

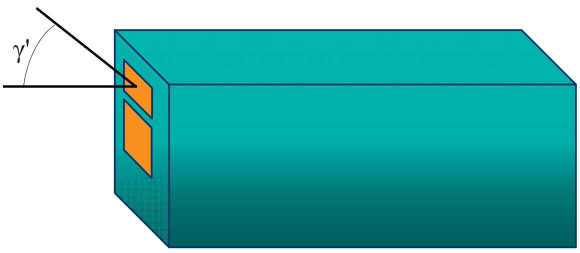


Figure 4-10 The viewing direction is given by the angle with respect to the horizontal plane.

To simplify the geometrical considerations, it is assumed that the blinds are flat and with zero thickness. In this special case, the spacing to width ratio (S/W) and the blind tilt will determine the free view fraction for different viewing directions.

Geometrical considerations can be used to derive the free view fraction as a function of viewing direction (γ'):

$$f(\gamma') = 1 + \frac{\cos\beta \cdot \tan\gamma' + \sin\beta}{S/W} \qquad \textit{for } \gamma' \geq -\beta \tag{4.5}$$

$$f(\gamma') = 1 - \frac{\cos\beta \cdot \tan\gamma' + \sin\beta}{S/W} \qquad \textit{for } \gamma' \leq -\beta \tag{4.6}$$

Similar relations were derived by Parmelee and Aubele (1952). However, in their work the free view fraction was named *Opening Ratio* and was discussed in relation to the transmittance properties of the blind assembly and not in relation to the viewing potential through the blinds.

Based on equations 4.5 and 4.6, the free view fraction for untilted and tilted blinds can be calculated. In Figure 4-11 the free view fraction for untilted blinds is given as a function of viewing direction (in degrees). As can be expected, the free view fraction is 1 in the horizontal viewing direction, and decreases symmetrically with higher/lower viewing direction angles. As can be seen from the graphs, the free view fraction is here in general larger for blinds with less overlap (high *S/W* ratios). Thus, for untilted blinds, decreasing the spacing to width ratio will reduce the viewing potential between the blind slats.

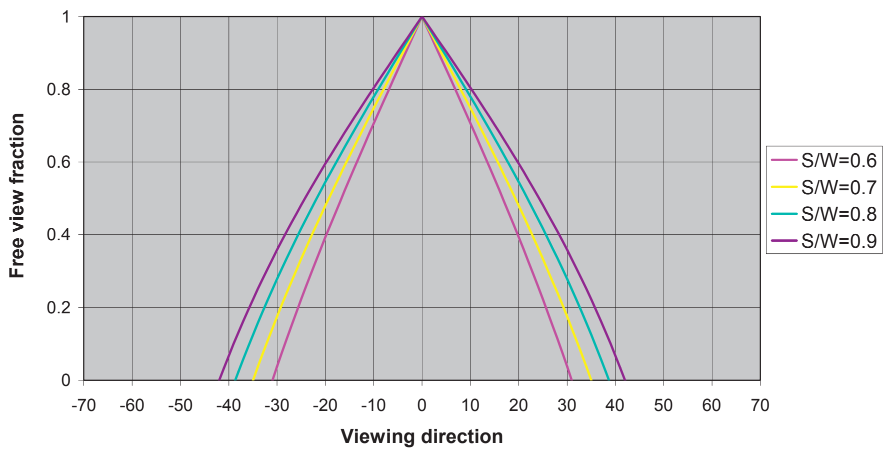


Figure 4-11 Free view fraction for untilted blinds of different spacing to width ratios.

In practice, at least for high latitudes, the blind slats are quite often tilted with a positive tilt angle (interior end of the slats upwards) in order to avoid direct sunlight from entering the interiors. In general, this (positive) tilting reduces the free view fraction in the upward viewing directions (positive angles). In the next figures the free view fraction is plotted for slat tilts (β) of 15º, 30º and 45º respectively.

In Figure 4-12 the viewing conditions when the blind slats are tilted 15º are shown. The viewing conditions are in general better for the largest *S/W*. The same applies for the blinds tilted 30º and 45º, as shown in Figure 4-13 and Figure 4-14 respectively.

For calculation of total solar energy transmittance, a blind tilt of 45º is often specified, as discussed in chapter 11. Based on this fact, it is especially interesting to look at the effect of spacing to width ratio on the free view factor when the blinds are tilted 45º. The results plotted in Figure 4-14 show that the viewing conditions in the horizontal direction are significantly better for the largest *S/W* for all upward viewing directions, and also for downward viewing directions down to -45º. For blinds tilted 45º it can be seen from the graphs that blinds with *S/W* = 0.7 (or lower) provide no free view in the horizontal direction, whereas blinds with *S/W* = 0.9 provide a free view fraction of more than 0.2 in the horizontal direction.

Negative tilting of the blinds also occurs in practice, but the graphs are not shown here. However, since the equations are symmetric, the free view fractions for negative tilts of 15º, 30º and 45º can be provided from the graphs for positive tilts simply by inverting the numbers on the x-axis.

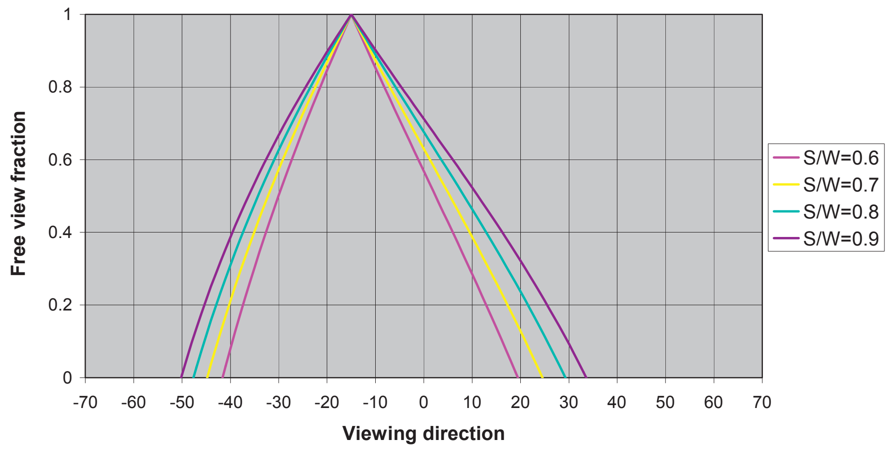


Figure 4-12 Free view fraction for blinds tilted 15º.

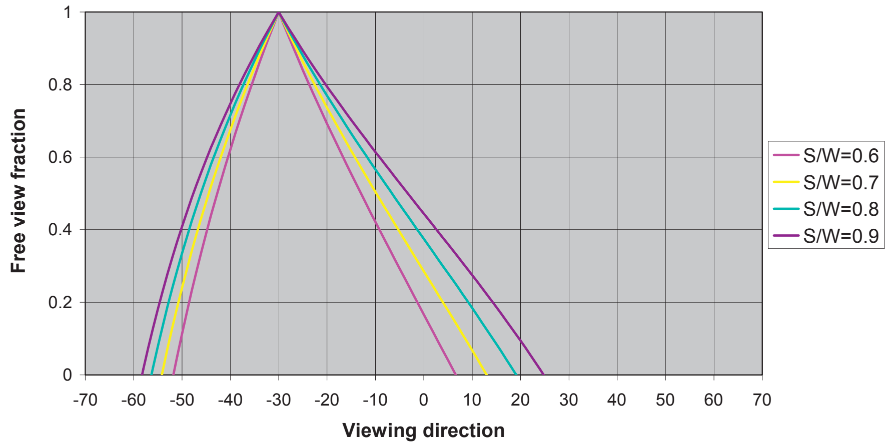


Figure 4-13 Free view fraction for blinds tilted 30º.

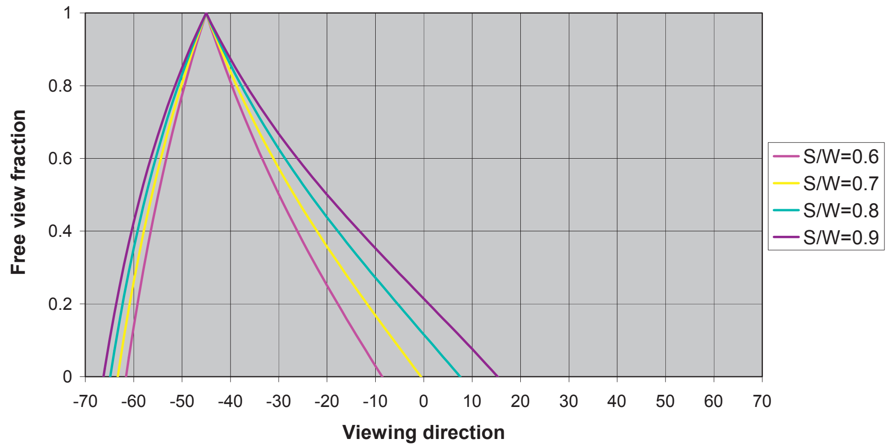


Figure 4-14 Free view fraction for blinds tilted 45º.

For some of the daylight scenes with low or intermediate projected solar elevation, the blinds need to be tilted (positive tilt) to obtain sunlight cut-off. In Figure 4-15 and Figure 4-16 the free view fraction for sunlight cut-off at projected solar elevations of 14.0º and 30.9º is shown. This corresponds to daylight scenes 3 and 5 respectively (see Table 4-2).

For these two scenes the free view fraction in the horizontal viewing direction is largest for the blinds with the lowest *S/W*. Based solely on the potential for horizontal view at blind tilt for sunlight cut-off, a blind with a low *S/W* should be preferred for these two scenes. For a projected solar elevation of 30.9º (scene 5), the blind with *S/W* of 0.6 can be kept more or less untilted, and a free view fraction close to 1.0 is obtained in the horizontal direction. The blind with *S/W* of 0.9 needs to be tilted to exclude direct sunlight, and the free view fraction in the horizontal viewing direction is reduced to 0.63.

For high sun scenes such as scene 8 (see Table 4-2), the blinds can be tilted with a negative tilt and still provide sunlight cut-off. The free view fraction in different viewing directions is shown in Figure 4-17. In this situation the blinds with the largest *S/W* provide the best viewing potential in the horizontal and downward directions. The blinds with the lowest *S/W* only provide the best viewing potential for positive viewing directions above 27º. For high sun scenes such as scene 8 it is also an option to keep the blinds untilted so as to enhance the viewing potential in the horizontal direction.

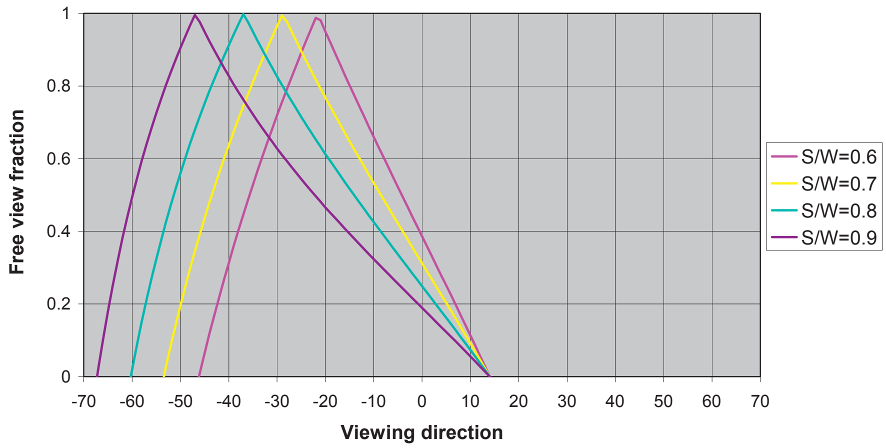


Figure 4-15 Free view fraction for sunlight cut-off at a projected solar elevation of 14.0º, corresponding to daylight scene 3.

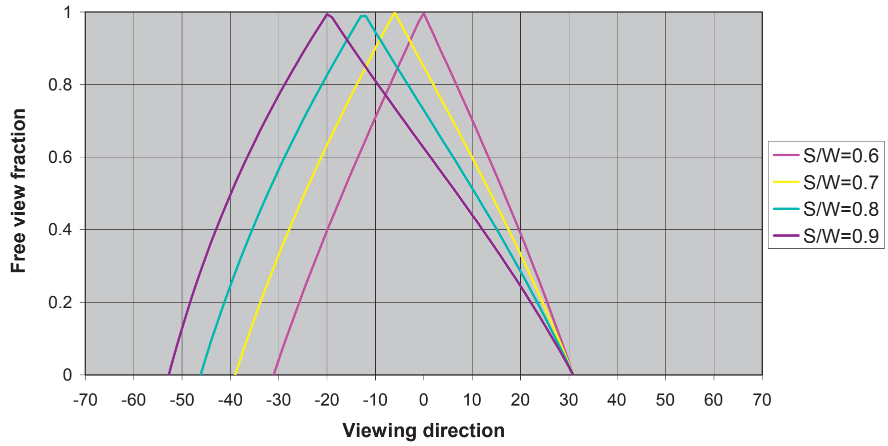


Figure 4-16 Free view fraction for sunlight cut-off at a projected solar elevation of 30.9º, corresponding to daylight scene 5.

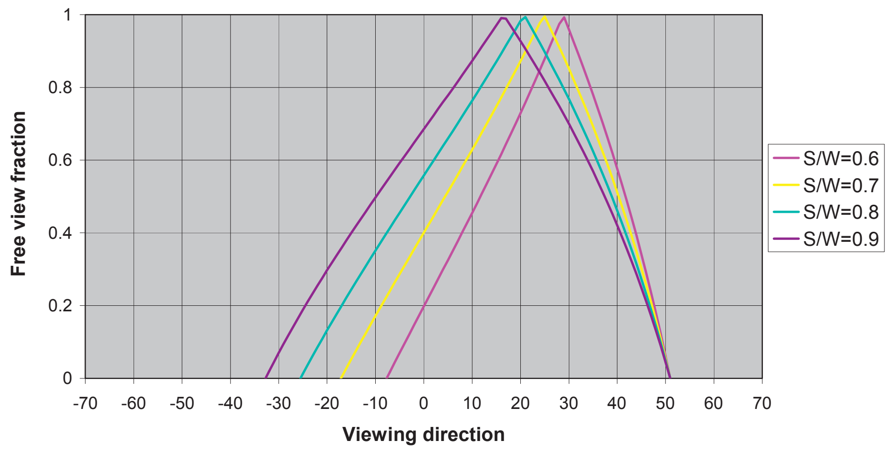


Figure 4-17 Free view fraction for sunlight cut-off at a projected solar elevation of 51.0º, corresponding to daylight scene 8.

In later chapters it is shown that tilting the blinds for direct sunlight cut-off is not always a guarantee for sufficient glare protection under sunny conditions. To reduce the window luminance to acceptable levels, it can in some cases be more appropriate to tilt the blinds to obtain a small (but still significant) free view fraction in a desired viewing directing (e.g. the horizontal direction). In Figure 4-18 the blinds are tilted to obtain a free view fraction of exactly 0.2 in the horizontal direction. The results show that in this situation, the blind with the highest *S/W* (of 0.9) gives slightly better viewing conditions for positive (upward) viewing directions, but slightly worse viewing conditions for negative (downward) viewing directions, down to about -35º in the shown situation.

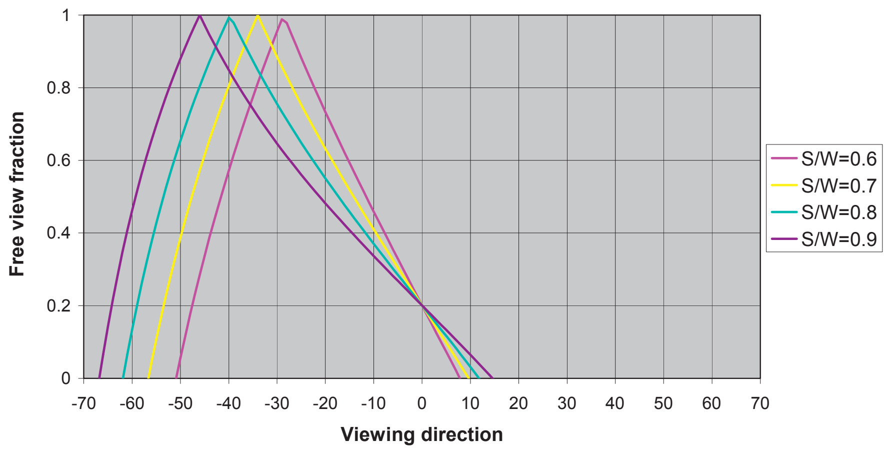


Figure 4-18 Free view fraction in different viewing directions when the blinds are tilted to obtain a free view fraction of exactly 0.2 in the horizontal direction.

4.8 Summary and conclusions

This chapter illustrates the importance of the blind geometry, and especially the spacing to width ratio (*S/W*). In general, a small *S/W* restricts the viewing potential of the building occupant, at least when the blinds of different *S/W* are all tilted at the same tilt angle.

However, the results of the geometrical investigations carried out also show that the cut-off tilt is very important for blinds and the tilt angle for sunlight cut-off varies with *S/W*. Blinds with small *S/W* can provide sunlight cut-off with less tilting, and less tilting enhances viewing potential in some directions. For low and intermediate sun conditions such as those of scene 3 and scene 5, the blind with low *S/W* provide the best viewing potential in the horizontal and upward directions, assuming that the blinds are tilted for sunlight cut-off. For high sun scenes such as scene 8, the situation is more complicated, and the best viewing potential in the upward directions depends on the specific viewing direction. Also, for high sun scenes it is a possibility to keep the blinds untilted while still blocking out direct sunlight, so as to enhance viewing potential in the horizontal direction.

An important reason for choosing a lower *S/W* in daylight redirecting blinds is the direction of specularly reflected sunlight when the blind are tilted for sunlight cut-off. As illustrated in Figure 4-8 the projected angle of reflected sunlight is in general lower for blinds with a lower *S/W*. This provides better opportunities for directing the sunlight far into the interiors where it is often needed the most.

5 Daylight simulations with TracePro

Computers are useless. They can only give you answers.

Pablo Picasso

5.1 Introduction

In the last decades, computer simulations have been used increasingly in design and evaluation of complex optical systems. One of the most important methods used is ray tracing. Ray tracing is a general technique that is based on the laws of geometrical optics. In ray tracing, the path of light rays through an optical system is followed, taking into account each rays interaction at optical interfaces. Ray tracing is used in the design of optical systems, such as telescopes and cameras. The term ray tracing is also applied to a rendering approach in computer graphics. There, ray tracing is used to visualise a modelled scene, using a technique which follows rays in the backward direction, starting with the eye-point, rather than originating at the light sources. Ray tracing methods starting at the light sources are often referred to as forward ray tracing, while ray tracing starting at the eye-point are referred to as backward ray tracing.

In daylight simulations, both forward and backward ray tracing has been applied extensively. Backward ray tracing is most suitable for photorealistic rendering. This method allows the user to determine a point in space and trace a large number of rays backwards onto the scene from this exact position, generating an image of the scene. One of the programs often used for daylighting simulations and rendering is Radiance. This program has been applied in several scientific works related to daylighting, including (Moeck 1998) and (Dubois 2001a). Radiance is based mainly on a backward ray tracing methodology.

For certain applications however, forward ray tracing is more suitable. With forward ray tracing it is more convenient to keep track of rays through a complicated optical system. One example from daylighting is the use of curved specular louvers. As described in the Radiance Manual on p. 579 (Ward and Shakespeare 1997), such a system is difficult to compute using a backward ray tracing methodology.

This chapter includes several mathematical equations that can be used to estimate the distribution of skylight and sunlight. In general, for this chapter, the angles provided in these equations can be assumed to be given in radians and not in degrees, unless otherwise is explicitly stated.

5.2 Forward ray tracing and fenestration systems

Ray tracing can be used to predict the optical performance of fenestration systems. With forward ray tracing it is possible to accurately model how daylight passes through a fenestration system and into the building interiors. From this, the lighting level and distribution within the interiors can be predicted. For venetian blind type solutions, the effect that several important parameters have on the lighting performance can be predicted. This could include the effect of the:

1. exterior light distribution (sky type).
2. optical properties of the glazing.
3. geometry of the blind (slat curvature, spacing, tilt, etc.).
4. optical properties of the blind surfaces.
5. geometry of the interiors, including daylight openings.
6. optical properties of the interior surfaces.

The use of forward ray tracing in analysing the daylighting performance of fenestration systems is discussed by Moeck and Yoon (2005). The first problem addressed by Moeck and Yoon is the generation of a ray distribution representing the light from the exterior environment. The second problem is the representation of the resulting light distribution at the exit surface of the fenestration system. The authors see several advantages if this light distribution can be represented as an intensity distribution in narrow angular increments in a photometric file format. Such a file could be imported to a lighting program and used to visualise the daylighting distribution in an interior space, the same way that such photometric data files are commonly applied to visualise the light distribution from electric luminaries.

Today, some of the advanced ray tracing programs applies both forward and backward ray tracing. This applies both to Radiance and TracePro. However, while Radiance is mainly based on backward ray tracing, TracePro relies mainly on forward ray tracing.

5.3 Introduction to TracePro

TracePro is a computer program developed by Lambda Research Corporation. According to the user manual (TracePro) p. 1.1, TracePro is a ray tracing program for optical analysis of solid models. TracePro allows you to launch rays into a model without making any assumptions as to the order in which objects and surfaces will be intersected. At each intersection, individual rays can be subjected to absorption, reflection, refraction, diffraction or scatter.

As described in the user manual (TracePro) on page 1.3, ray tracing in TracePro is based on the so-called Monte Carlo method. This means that the propagation of the traced rays are treated as a random process using the scattering distribution as a probability density. In "brute force" Monte Carlo ray tracing, the directions of rays are chosen randomly, and a reliable answer is obtained by tracing a very large number of rays. TracePro makes use of so-called variance reduction techniques to reduce the number of rays required in order to obtain a reliable result.

Also, in order to limit the number of rays accounted for in a TracePro simulation, rays are terminated when the flux reaches a certain threshold value as compared to the starting flux of the original incident ray. In the simulations that follows, a flux threshold of 0.01 was used for ray termination, meaning that a ray is terminated if the flux associated with that ray drops to less than 1% of the starting flux.

TracePro can be described by outlining the steps that are typically taken when you start a new TracePro project. According to the user manual these are: (1) creating a solid model, (2) defining properties, (3) applying properties, (4) ray tracing, and (5) analysis.

It should be noted that TracePro has the capability to handle light sources of a given spectral distribution, as well as different types of polarisation. For the work presented in the following, one wavelength of unpolarised light has been considered sufficient.

5.4 The daylight source

The light from the sun is the primary source of all daylight. Outside the Earth's atmosphere, sunlight travels in straight lines from the sun. When sunlight enters the Earth's atmosphere, it interacts with components that are present in the atmosphere. Some of these components reflect sunlight. Other components absorb or scatter the light, thus creating diffuse light from the sky. A part of the direct sunlight and diffuse skylight that reaches the ground is reflected, creating ground reflected light.

Following from this, and as shown in Figure 5-1, the daylight source consists of three main components; direct sunlight, diffuse skylight and ground reflected light. Thus, the global exterior illuminance, E_{glob}, falling on any surface is composed of a direct component, E_{dir}, a diffuse skylight component, E_{diff}, and a ground reflected component, E_{gr}, giving the following equation:

$$E_{glob} = E_{dir} + E_{diff} + E_{gr} \quad (5.1)$$

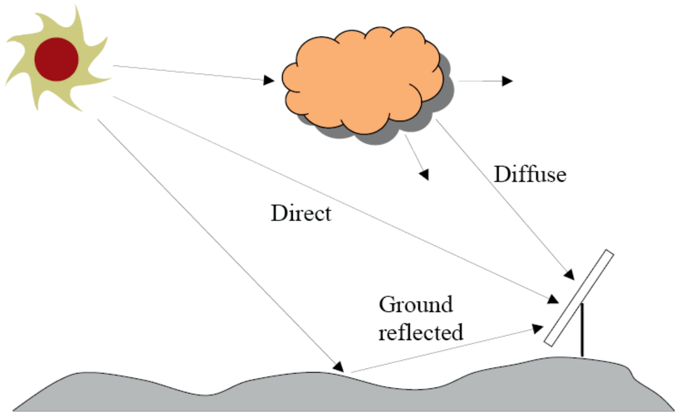


Figure 5-1 The daylight source. The daylight incident on a surface can be divided into three main components; direct sunlight, diffuse skylight and ground reflected light.

5.4.1 Sky luminance distributions

The luminance distribution of the sky depends on weather and climate, and it changes during the course of a day with the position of the sun. However, it is practical to define a set of standard reference luminance distributions to represent the most common sky conditions. The mathematical description that follows is mainly based on CIE publication 110-1994 "Spatial Distribution of Daylight – Luminance distributions of Various Reference Skies" (CIE 1994) as well as on a publication by Löfberg (1976).

The given luminance distributions are all symmetrical about the solar meridian and they are defined by smooth continuous functions. According to an ISO standard on this subject (ISO 2004), such distributions are typical of cloudless skies and of those where the cloud cover is homogeneous. The distributions are based on empirical studies, providing an approximation to real skies that is sufficiently accurate for many practical daylight calculation purposes.

5.4.1.1 The overcast sky

The mathematically simplest luminance distribution is known as the uniform sky, or sky of uniform luminance. It is given by the following simple relation where L_a is the luminance of a sky element, and L_z is the zenith luminance.

$$L_a = L_z \quad (5.2)$$

However, for the overcast sky, measurements have shown that the sky luminance varies with the elevation above the horizon (γ). The equation below was proposed by Moon and Spencer (1942) and has since then been used extensively in daylighting calculations. The equation includes the elevation angle of a sky element (γ) as defined by Figure 4-1. The assumption behind this equation is that the luminance from zenith to horizon decreases in such a way that the zenith is three times brighter than the horizon. Today, this distribution is known as the CIE Traditional Overcast Sky:

$$L_a = L_z \cdot \frac{1 + 2 \cdot \sin\gamma}{3} \quad (5.3)$$

The zenith luminance of the overcast sky could depend on several factors, including solar elevation (γ_s), cloud thickness and ground reflectance. Several equations have been proposed to describe the zenith luminance, as indicated in CIE publication 110 (CIE 1994). Krochmann proposed the following simple equation that is independent of cloud thickness and ground reflectance:

$$L_z = 123 + 8600 \cdot \sin\gamma_s \quad [\mathrm{cd/m^2}] \quad (5.4)$$

5.4.1.2 The clear sky

The luminance distribution of the clear sky is quite complicated. Studies have shown that the brightest area of the clear sky is located near the sun. The darkest area is to be found about 90 degrees from the sun, on the other side of zenith. Contrary to the overcast sky, the horizon is somewhat brighter than the zenith luminance. According to CIE (1994), the luminance distribution of the clear sky can be described by the following equation:

$$L_a = L_z \cdot \frac{(0{,}91 + 10 \cdot e^{-3\chi} + 0{,}45 \cdot \cos^2\chi) \cdot (1 - e^{-\frac{0{,}32}{\sin\gamma}})}{(0{,}91 + 10 \cdot e^{-3(\frac{\pi}{2} - \gamma_s)} + 0{,}45 \cdot \sin^2\gamma_s) \cdot (1 - e^{-0{,}32})} \quad (5.5)$$

Where χ is the angle between the sky element and the sun, given by the equation:

$$\chi = \arccos\,(\sin\gamma_s \cdot \sin\gamma + \cos\gamma_s \cdot \cos\gamma \cdot \cos[\alpha - \alpha_s]) \qquad (5.6)$$

Several equations have been proposed to describe the zenith luminance of the clear sky, and eight of these equations are given in CIE (1994). According to the equation proposed by Krochmann, the zenith luminance can be calculated from the following equation:

$$L_z = 100 + 63 \cdot \gamma_s + \gamma_s \cdot (\gamma_s - 30) \cdot e^{0{,}0346 \cdot (\gamma_s - 68)} \quad [\mathrm{cd/m^2}] \qquad (5.7)$$

In this equation, γ_s is given in degrees.

5.4.2 Illuminance on horizontal and vertical surfaces

The illuminance from direct sunlight or diffuse skylight has been measured on horizontal and vertical surfaces at many different geographic locations. Equations that predict the illuminance on horizontal surfaces for different sky types and solar elevations have been proposed. It is also possible to calculate illuminance values based on the equations for luminance distribution and zenith luminance. In the following sections, some equations for illuminance on horizontal and vertical surfaces will be given. The equations apply for direct sunlight as well as diffuse skylight from clear or overcast skies.

5.4.2.1 Illuminance from direct sunlight

To a fairly good approximation, the sun acts as a black body emitter of radiation at a temperature close to 5900 K. The resulting illuminance outside the Earth's atmosphere on a surface perpendicular to the sun beam is known as the solar illuminance constant, E_{sol_const}. This was defined by Dogniaux et. al (1967) to be 126.820 lux. As the direct sunlight passes through the Earth's atmosphere the intensity of the light will decrease. The air mass, the atmospheric extinction coefficient and the turbidity factor are parameters used to describe and quantify direct sunlight at the Earth's surface.

A rule of thumb states that, on a clear day with high sun, the illuminance from direct sunlight (E_{dir}) is approximately 100 klux on a surface at ground level that is perpendicular to the direction of the sun. For lower sun elevations the illuminance will drop due to the increasing air mass of the atmosphere.

According to CIE publication 20 (CIE 1972) the direct illuminance on a surface at ground level that is perpendicular to the sun is given by:

$$E_{dir\_perp} = 130 \cdot e^{-\frac{0.2}{\sin \gamma_s}} \quad \text{[klux]} \tag{5.8}$$

When the surface is not perpendicular to the sun, the illuminance will drop with the angle of incidence (θ) of sunlight on the surface according to the following equation:

$$E_{dir} = E_{dir\_perp} \cdot \cos\theta \tag{5.9}$$

Following from this, the direct illuminance on a horizontal surface at ground level is given by:

$$E_{dir\_hor} = 130 \cdot \sin\gamma_s \cdot e^{-\frac{0.2}{\sin \gamma_s}} \quad \text{[klux]} \tag{5.10}$$

On a vertical window facade, the angle of incidence of direct sunlight can be calculated from the elevation angle of the sun (γ_s) and the azimuth difference ($\Delta\alpha_s$) between the sun and window orientation according to the following equation:

$$\cos\theta = \cos\gamma_s \cdot \cos\Delta\alpha_s \tag{5.11}$$

Resulting from this, the direct illuminance on a vertical surface at ground level is given by:

$$E_{dir\_vert} = 130 \cdot e^{-\frac{0.2}{\sin \gamma_s}} \cdot \cos\gamma_s \cdot \cos\Delta\alpha_s \quad \text{[klux]} \tag{5.12}$$

5.4.2.2 Illuminance from the overcast sky

Several equations have been proposed to describe the illuminance on the ground from an overcast sky. Measurements in Sweden from the years 1965 to 1969 have been analysed. Based on these measurements, according to Löfberg (1976), the illuminance from the overcast sky on a horizontal surface can be approximated by the equation:

$$E_{hor} = 0{,}44 + 0{,}48 \cdot \gamma_s \quad \text{[klux]} \tag{5.13}$$

In this equation, γ_s is given in degrees.

Note that the equation above is based on measurements of light incident onto a horizontal detector. It does not imply a specific luminance distribution of the overcast sky.

It is however also possible to calculate the horizontal illuminance from the sky based on integration over the luminance distribution. For the overcast sky the luminance distribution is given by the CIE Traditional Overcast Sky distribution, equation 5.3. For an unobstructed sky we have:

$$E_{hor} = \int_0^{\pi/2} \int_0^{2\pi} L_z \cdot \sin\gamma \cdot \cos\gamma \cdot \left(\frac{1 + 2 \cdot \sin\gamma}{3} \right) d\alpha \, d\gamma = \frac{7}{9} \cdot \pi \cdot L_z \tag{5.14}$$

Inserting the zenith luminance as given by Krochmann (equation 5.4) then gives:

$$E_{hor} = \frac{7}{9} \cdot \pi \cdot (0.123 + 8.6 \cdot \sin\gamma_s) \quad \text{[klux]} \tag{5.15}$$

This equation is quite different from equation 5.13 above. This illustrates the fact that measurements of the illuminance on the ground from an overcast sky at different locations have shown a large variance.

A similar approach can be used to calculate the illuminance from the overcast sky on a vertical plane:

$$E_{ver} = \int_{0}^{\pi/2} \int_{-90}^{2\pi} L_z \cdot \cos\alpha \cdot \cos^2\gamma \cdot \left(\frac{1+2\cdot\sin\gamma}{3}\right) d\alpha\, d\gamma = \left(\frac{\pi}{6}+\frac{4}{9}\right)\cdot L_z \qquad (5.16)$$

5.4.2.3 Illuminance from clear sky

According to Löfberg (1976), the illuminance from the clear sky (not including direct sunlight) on a horizontal surface can be approximated by the equation:

$$E_{hor} = 1{,}1 + 15{,}5 \cdot \sqrt{\sin\gamma_s} \quad \text{[klux]} \qquad (5.17)$$

When the luminance distribution of the clear sky is known, the illuminance contribution from the sky (not including direct sunlight) on a horizontal or vertical surface can be calculated by integration. Using the same approach as for the overcast sky, the following integrals are obtained:

$$E_{hor} = \int_{0}^{\pi/2} \int_{0}^{2\pi} \sin\gamma \cdot \cos\gamma \cdot L_a \, d\alpha\, d\gamma \qquad (5.18)$$

$$E_{ver} = \int_{0}^{\pi/2} \int_{-\pi/2}^{\pi/2} \cos\alpha \cdot \cos^2\gamma \cdot L_a \, d\alpha\, d\gamma \qquad (5.19)$$

For the clear sky the equation for L_a is relatively complicated (see equation 5.5.). This makes it hard to solve the integrals analytically, but the given integrals can easily be solved numerically.

5.5 Daylight modelling in TracePro

Most ray tracing software used for daylighting calculations have built-in distributions representing various types of skies. Two examples of this are the software Radiance and the software Relux. Unfortunately, this feature is not available in the current version of TracePro. However, it is possible in TracePro to construct a ray file that represents the light from the sun, sky and exterior surroundings. A ray file in TracePro consists of a set of rays, where each ray is defined by seven parameters; three starting coordinates (x, y and z), three direction vectors (x, y and z), as well as the luminous flux of the ray.

For a vertical window facade, it is useful to set up a grid of rays with starting positions in a plane located on the exterior side of the window opening, with direction vectors pointing towards the interior and with an intensity distribution given by the exterior daylight conditions (such as sky luminance and ground luminance).

A procedure to generate an intensity distribution from an arbitrary exterior hemispherical luminance map is outlined by Moeck and Yoon (2005). A similar procedure is used here, taking advantage of the possibilities to generate so-called grid sources in TracePro.

5.5.1 Calculation of ray flux from luminance distribution

The daylight that is incident on a vertical window opening has a distribution that can be calculated from the sky models described in the preceding sections. To represent the daylight, a ray file can be constructed with ray starting positions on the exterior side of the window opening. The ray file can be set up to generate rays in all directions pointing towards the window plane, with a uniform angular profile. The flux of each ray can be calculated from the exterior luminance in the direction from where the ray originates; that is, the opposite of the ray direction. Downward directed rays will originate from a patch of the sky, while upward directed rays will originate from the ground.

According to Moeck and Yoon (2005), the solid angle surrounding each ray is approximated by:

$$d\Omega = 2\pi/n \tag{5.20}$$

where $d\Omega$ is the solid angle surrounding a ray, 2π is the solid angle of the full hemisphere comprising the interiors, and *n* is the number of rays.

As long as the area (A_{win}) of the window opening is small compared to the exterior surroundings, the intensity of each ray can be calculated by:

$$I = L \cdot A_{win} \cdot \cos\theta \qquad (5.21)$$

where I is the intensity of a ray with luminous flux $d\Phi$, L is the luminance of a small patch of sky or ground, and θ is the angle between the surface normal of the window opening and the direction to an exterior hemisphere element with luminance L.

By definition:

$$I = \frac{d\Phi}{d\Omega} \qquad (5.22)$$

From this, it follows that the luminous flux $d\Phi$ of each ray is given by:

$$d\Phi = d\Omega \cdot I = \frac{2\pi \cdot L \cdot A_{win} \cdot \cos\theta}{n} \qquad (5.23)$$

5.5.2 Ray flux from overcast sky, clear sky and ground

For the overcast sky, the luminance in a given direction is given by equations 5.3 and 5.4, and for the clear sky it is given by equations 5.5 and 5.7. The flux of any ray originating from a sky patch can be calculated by equation 5.23 above.

Rays originating from the ground will have a flux that can be calculated similarly from the luminance of the ground. It is assumed that the ground is a lambertian reflective surface. The luminance from the ground (L_{ground}) will then be the same in every viewing direction. The ground luminance can be calculated from the illuminance on the ground (E_{ground}) and the ground reflectance (ρ) by the following relation, applicable for lambertian surfaces:

$$L_{ground} = \frac{\rho}{\pi} \cdot E_{ground} \qquad (5.24)$$

It remains to calculate the illuminance on the ground. For this, it would be possible to use the equations for ground illuminance from overcast sky and clear sky (without sunlight) given by equations 5.13 and 5.17. However, a more coherent approach is to calculate the ground illuminance by integrating over the given sky luminance distributions. With this approach only the sky luminance distributions are used and no additional equations are needed.

The illuminance on the ground from an unobstructed overcast sky is therefore calculated by equation 5.15.

For clear skies with sunlight, both the direct sunlight and the diffuse light from the sky contribute to the illuminance on the ground. The contribution from the unobstructed clear sky (excluding direct sunlight) is calculated by numerically solving the integral in equation 5.18, including the luminance distribution from equation 5.5 and the zenith luminance from equation 5.7. The contribution from direct sunlight is given by equation 5.10. It follows that the illuminance on the ground from unobstructed clear sky with sun is given by:

$$E_{ground} = \int_0^{\pi/2} \int_0^{2\pi} \sin\gamma \cdot \cos\gamma \cdot L_a \, d\alpha \, d\gamma + 130 \cdot \sin\gamma_s \cdot e^{-\frac{0.2}{\sin\gamma_s}} \qquad (5.25)$$

where L_a is given by equations 5.5 and 5.7.

5.5.3 Ray flux from direct sunlight

Direct sunlight can be represented in TracePro by a so-called grid source.

The illuminance on a vertical plane from direct sunlight will wary according to the position of the sun relative to the plane. The illuminance from direct sunlight can be used to calculate the flux of the individual rays that represent sunlight in the grid source. The illuminance from sunlight on the ground is given by equation 5.10, and the illuminance on a vertical plane is given by equation 5.12.

When the illuminance is constant over an area (*A*), as is the case for unobstructed direct sunlight on a window opening, the luminous flux is given by the simple relation below:

$$\Phi = E \cdot A \qquad (5.26)$$

The flux of individual rays (dΦ) is given by:

$$d\Phi = \frac{\Phi}{n} = \frac{E \cdot A}{n} \qquad (5.27)$$

where *n* is the number of rays in the grid source and *A* is the area of the grid.

5.5.4 Construction of ray files

The next step is to generate TracePro ray files representing a chosen daylight condition and with boundaries adjusted so as to correspond with the two window openings of the reference space described in section 6.2. A relatively simple approach is used for direct sunlight and a slightly more complicated approach is used for diffuse skylight and ground reflected light.

5.5.4.1 Ray files for direct sunlight

For direct sunlight it is relatively straightforward to generate a ray file that represents the sunlight incident upon a vertical window opening. As indicated above, a so-called grid source can be set up, and TracePro allows the user to define the shape and dimensions of the boundary of a planar grid that represents the starting points for rays. The user is also allowed to choose between different grid patterns. A so-called random grid can be used to generate rays with arbitrary starting positions within the grid boundaries.

After the boundary has been set up, the user can choose the number of rays in the grid as well as the individual ray flux. It is possible to choose between different angular beam profiles. Parallel rays can be set up by choosing a *uniform* angular profile with a half angle of zero. It is also possible to choose a *solar* angular profile to set up an angular profile equal to that measured for the sun (a beam with a divergence of approximately 0.5º). The direction of the parallel rays can be chosen by inserting angles corresponding to solar elevation and azimuth angles. After the dimensions of the grid and the number of rays have been chosen, the individual ray flux is specified. This ray flux can be calculated from equation 5.27, inserting the vertical illuminance value as calculated from equation 5.12.

5.5.4.2 Ray files for diffuse skylight and ground reflected light

The procedure to generate ray files representing diffuse skylight and ground reflected light is more complicated. It is again convenient to start with the generation of a grid source with grid boundaries adjusted to the window openings and random ray starting positions within the grid. This time, however, a uniform angular distribution with half angle of 90º is chosen. The beam orientation can be directed inwards along the window normal. This procedure generates a set of rays with equal ray flux pointing towards the interior. It remains to adjust the ray flux in each direction according to the luminance of the exterior in that direction. The ray flux is calculated by the use of equation 5.23.

All rays pointing upwards are assumed to originate from the ground, and the luminance value to be used in equation 5.23 is here calculated from equation 5.24. The ground luminance used in 5.24 is calculated from equation 5.15 for overcast sky and 5.18 for clear skies.

Rays pointing downwards are assumed to originate from the sky. For these rays, the luminance values to be used in 5.23 are calculated from equations 5.3 and 5.4 for overcast sky and from 5.5 and 5.7 for clear skies.

The described modification of the individual ray flux can not be carried out directly in TracePro. The grid source ray files are therefore imported into a spreadsheet (Excel) and modified there. After this modification, the ray files are imported back into TracePro.

5.5.5 Daylight scenes

For most daylighting simulation software, the user specifies a geographic location, date, time of day and sky condition, and from this input the program then calculates the daylight source. As described earlier, the current version of the software TracePro does not have this functionality. However, in the previous sections it is described a method for generating ray sources with distributions that represent a mathematically described daylight scene. This method can be used to generate TracePro source files to be used for evaluating daylighting systems positioned in vertical window openings lit by light from the overcast sky or from clear skies with sun. For practical purposes a limited set of sky scenes are selected, representing a total of 10 scenes that are considered relevant for high latitudes.

5.5.5.1 Overcast sky

First of all, a scene with overcast sky is selected (scene 1). Here, the daylight distribution is independent of the solar azimuth. The solar elevation only influences the absolute value of the daylight source, not the relative distribution. Since the main purpose of the simulations is to compare different daylighting systems, the absolute values will not be critical. Hence, only one solar elevation will suffice, and 30º is selected as a typical intermediate solar elevation value for high latitudes. The overcast sky scene is commonly applied to evaluate the daylight performance of buildings, for example through the calculation of daylight factors.

5.5.5.2 Clear skies

For clear skies, three different solar elevations are selected as well as three different solar azimuth angles, relative to that of the window normal. Combining the three solar elevations and the three azimuth angles gives a total of nine scenes with different sun positions relative to that of the window normal.

The three solar elevation values are selected to represent low sun conditions, intermediate sun conditions and high sun conditions (for high latitudes). The selected solar elevation angles values are 10º, 30º and 50º respectively.

The three azimuth angles relative to the window normal are selected to represent near to normal azimuthal incidence, intermediately inclined azimuthal incidence and oblique azimuthal incidence. The selected azimuth angles relative to the direction of the window normal are 15º, 45º and 75º respectively.

A sun path chart as that shown in Figure 5-2 can be used to indicate at what time of year and at what hour of the day the different solar elevation angles are present. The chart shows solar time, which deviates slightly from local time and does not account for daylight-saving time. At an approximate level the chart is still very useful in providing information about solar elevation angles.

The chart generated for Oslo show that at this latitude a solar elevation of 50º is only present in a two month period around the summer solstice; approximately from May 21st to July 21st and only at times around midday.

The solar elevation of 30º is reached at midday at the equinox (March 20th or September 23rd). If we assume that the working hours are within the time frame from 06.00 to 18.00 the chart shows that the solar elevation of 30º is present at some time during these hours for all the 6 summer months.

The solar elevation of 10º is reached at midday on January 21st. The sun chart also indicates that, during the hours from 06.00 to 18.00 the low sun elevation of 10º is present until about April 20th in the spring season.

From this it can be concluded that the intermediate sun elevation of 30º occurs much more frequently during the office hours than the high sun elevation (50º). The low sun elevation (10º) can occur during the two 3 month periods from January 21st to April 20th and from August 23rd to November 22nd. However, the likelihood of external shading obstructing the sun at an elevation of 10º is much higher than for the sun located at 30º. Therefore, the choice of a solar elevation of 30º representing an intermediate solar elevation angle seems appropriate for this latitude.

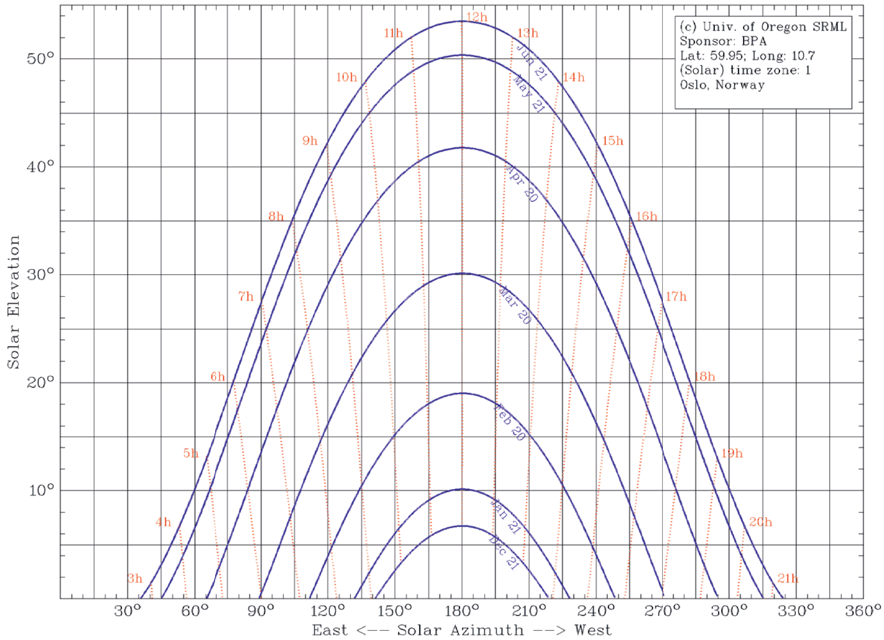


Figure 5-2 Sun chart for Oslo, Norway generated by the Sun path chart program available on the web-site of the University of Oregon (www.solardat.uoregon.edu).

5.5.5.3 Summary of daylight scenes

The table below summarizes all of the 10 daylight scenes. Of the clear sky scenes, 2 to 4 represent low sun scenes, 5 to 7 represent intermediate sun elevation and 8 to 10 represent high sun scenes.

Table 5-1 Summary of daylight scenes 1 to 10. The azimuth difference is the difference in azimuth angle between the sun and the window normal.

Scene	Sky type	Solar elevation	Azimuth difference
1	overcast sky	30°	not relevant
2	clear, low sun	10°	15°
3	clear, low sun	10°	45°
4	clear, low sun	10°	75°
5	clear, int. sun	30°	15°
6	clear, int. sun	30°	45°
7	clear, int. sun	30°	75°
8	clear, high sun	50°	15°
9	clear, high sun	50°	45°
10	clear, high sun	50°	75°

5.5.5.4 Ground illuminance for daylight scenes

The ground illuminance will wary according to sky type and solar elevation. These parameters will therefore influence the flux of the rays representing light reflected from the ground. As explained in earlier sections, the ground illuminance is needed as input in the generation of TracePro ray files to represent the different daylight scenes. It is also shown earlier that both the diffuse skylight as well as the direct sunlight contributes to the ground illuminance.

For the overcast sky scene there is no direct sunlight, and the ground illuminance is given by equation 5.15. For the solar elevation of 30º we get E_{ground} = 10807 lux.

For the clear sky scenes, the ground illuminance can be calculated from equation 5.25. The integral representing the contribution from the clear skies can be solved numerically. The software MATLAB is used to obtain values for the diffuse component of the ground illuminance for each of the 9 clear sky scenes.

The table below summarizes the ground illuminance for all of the 10 daylight scenes.

Table 5-2 Ground illuminance for 10 different daylight scenes.

Scene	Sky type	E_{diff} [lux]	E_{dir} [lux]	E_{ground} [lux]
1	overcast	10 807	0	10 807
2, 3, 4	clear, low sun	5 083	7 135	12 218
5, 6, 7	clear, int. sun	12 725	43 571	56 296
8, 9, 10	clear, high sun	16 210	76 703	92 913

5.6 Validation of TracePro ray files

In earlier sections a method is described that can be used to generate ray files representing daylight from overcast sky and clear skies with arbitrary sun positions. Based on the described method, ray files representing 10 different daylight scenes are created. In this section the outlined method is validated. The validation is mainly based on comparing illuminance values obtained from TracePro simulations to values obtained by mathematical calculations.

5.6.1 Validation of ground illuminance

The ground illuminance given in Table 5-2 is used as input to the ground reflected component in the TracePro ray files. The ground illuminance values are in part obtained by integrating the luminance values of the sky. It should be noted that this method for obtaining ground illuminance is rather unusual, especially for clear sky conditions. This method will henceforth be called the "integration approach". As explained earlier, this method is chosen for coherence, to limit the number of equations used as input in the daylight modelling. It is of interest to compare the integration approach with values obtained by some of the equations that have been proposed to calculate ground illuminance.

5.6.1.1 Ground illuminance for overcast sky

For the overcast sky scene (S1) the integration approach gives a value for ground illuminance of 10807 lux. The equation proposed by Löfberg (1976), equation 5.13, gives a value of 14840 lux. As shown by Löfberg, there is a large variation in ground illuminance values as obtained from different sources. In the figure below, the integration approach is compared with results from equation **Error! Reference source not found.**5.13. Results obtained from the software Relux are also included for comparison.

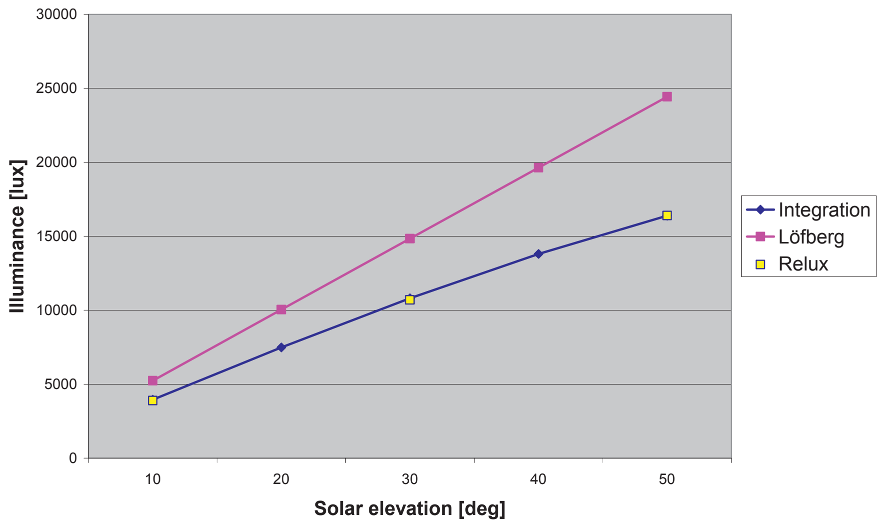


Figure 5-3 Ground illuminance from overcast sky obtained by different approaches.

It is seen that the integration approach gives values that are very similar to the values obtained by Relux. The results indicate that the integration approach is also used as a mathematical basis in the software Relux.

5.6.1.2 Ground illuminance for clear sky with sun

According to Löfberg, different equations have been proposed to calculate the ground illuminance for clear skies with sun. Based on measurements carried out in Stockholm in 1965-69, the following approximation is proposed by Löfberg:

$$E_{ground} = 0{,}7 + 1{,}5 \cdot \gamma_s \quad \text{[klux]} \qquad (5.28)$$

In this equation, γ_s is given in degrees.

Kittler has proposed the following equation:

$$E_{ground} = 45 \cdot (1 + 1{,}5 \cdot \sin\gamma_s) \cdot \sin\gamma_s \quad \text{[klux]} \qquad (5.29)$$

In the figure below, values obtained by the integration approach (equation 5.25) are compared to values obtained by the equations from Löfberg and Kittler, as well as simulation results from the software Relux.

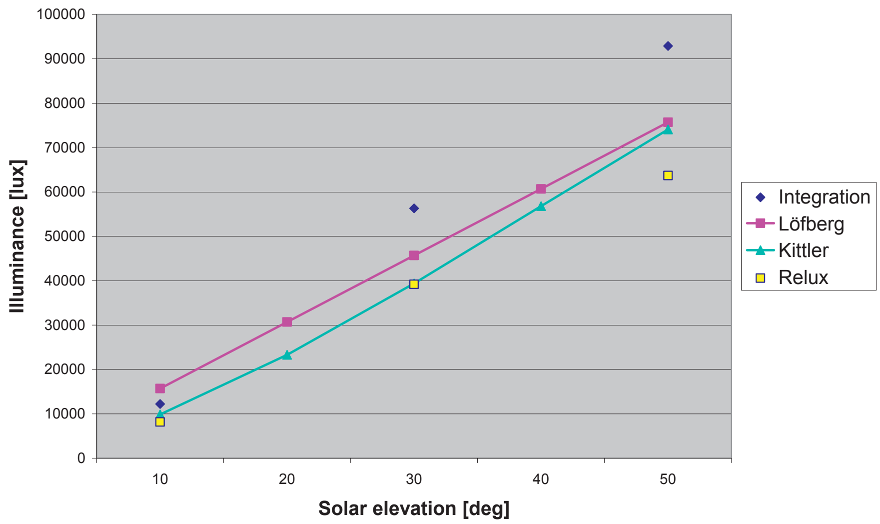


Figure 5-4 Ground illuminance from clear sky with sun obtained by different approaches.

Notice that for high solar elevations, the ground illuminances obtained with the integration approach are higher than the values obtained by other approaches. This is in complete accordance with expectations, as shown by Löfberg. Löfberg shows that the results based on equations from CIE give the highest values for ground illuminance at high solar elevations. As indicated by Löfberg, the deviation in results based on different equations is rather large; up to about 40% and even more for some solar elevations. This is most likely a reflection of large variations in measurement results, caused by seasonal and climatic variations in atmospheric conditions.

5.6.2 Validation of vertical illuminance

The TracePro ray files are constructed to give the correct light distribution on a vertical plane. The vertical illuminance on the plane of the window opening can therefore be used to directly compare the results from TracePro simulations with other approaches. It is to be expected that values from TracePro are similar to values obtained by the mathematical "integration approach", on which the TracePro ray files are based.

5.6.2.1 Vertical illuminance from TracePro simulations

As explained in earlier sections, TracePro ray files are constructed that represent the daylight from each of the 10 daylight scenes in Table 5-1. For all daylight scenes, the diffuse skylight and ground reflected light is combined in one ray file and the direct sunlight is generated by a different ray file. An exception is scene 1, where no sunlight is required. A set of 30 000 rays are generated for both types of ray files. This means that the total number of rays traced is 30 000 for scene 1, and 60 000 for scenes 2 to 10. To generate the ground reflected component, a ground reflectance of 0.2 is assumed.

For each of the daylight scenes, the user can initiate a ray trace with a single ray file or with two ray files in combination. In this way it is possible to obtain vertical illuminance values for the direct sunlight component only, for diffuse skylight plus ground reflected light only, or for the combination of these to; the global vertical illuminance.

5.6.2.2 Vertical illuminance by the integration approach

Each of the vertical illuminance components can be calculated mathematically. The direct sunlight component can be calculated from equation 5.12. The diffuse skylight component can be calculated from equations 5.16 (overcast sky) and 5.19 (clear skies) respectively. The ground reflected component can be calculated in similar fashion, by solving the following integral, where L_{ground} is given by equation 5.24:

$$E_{ver} = \int_{-\pi/2}^{0} \int_{-\pi/2}^{\pi/2} L_{ground} \cdot \cos\alpha \cdot \cos^2\gamma \; d\alpha \; d\gamma = L_{ground} \cdot \frac{\pi}{2} \quad (5.30)$$

5.6.2.3 Vertical illuminance results

The results from TracePro simulations and from the mathematical calculations are given in Table 5-3. The indirect component of the vertical illuminance includes diffuse skylight as well as ground reflected light. Note that for the clear sky scenes the ground reflected light also includes direct sunlight reflected off from the ground. The direct component includes direct sunlight only.

Table 5-3 Vertical illuminance for different daylight scenes obtained by TracePro simulations and by mathematical calculations.

Scene	Indirect component			Direct component		
	TracePro [lux]	Integration [lux]	Diff. [%]	TracePro [lux]	CIE [lux]	Diff. [%]
1	5285	5362	1.4	-	-	-
2	8754	8867	1.3	39088	39088	0.00
3	7441	7489	0.7	28614	28614	0.00
4	5367	5416	0.9	10473	10473	0.00
5	20715	20981	1.3	72895	72895	0.00
6	18145	18354	1.1	53363	53363	0.00
7	14282	14421	1.0	19530	19532	0.01
8	23093	23403	1.3	62164	62168	0.01
9	21161	21455	1.4	45507	45510	0.01
10	18332	18551	1.2	16654	16658	0.02

The results show that there is an almost perfect agreement between the theoretical results and the TracePro simulation results for the direct sunlight component.

For the indirect component, the differences are somewhat larger but consistently less than 1.5%. These differences between the mathematical calculations and TracePro simulations (for the indirect component) are most likely caused by the computer program's use of a random generator (hence Monte Carlo simulations!) for the construction of the ray files. Evidently, even with 30 000 rays, statistical deviations occur. However, these deviations of less than 1.5% are considered quite acceptable here, keeping in mind the large variations between different sky models seen in previous sections.

5.7 Summary and conclusions

The main aim of the work presented in this chapter was to construct TracePro ray files that can be used to represent light from different sky scenes incident onto a vertical window opening.

Ray files for 10 different sky scenes have been constructed according to a mathematical description of the sky. The ray files include the contributions from the sky, the ground, as well as the direct radiation from the sun.

To validate the constructed ray files the vertical illuminance (on the window opening) obtained from TracePro simulations have been compared to values that are obtained analytically. The results from the TracePro simulations of the 10 scenes indicate that all the constructed ray files are in accordance with the mathematical sky models used as a basis for the ray files.

It is considered unlikely that the vertical illuminance obtained by the simulations would be correct unless the light distribution also is correct. Nevertheless, a further validation of the constructed ray files representing 10 different sky scenes are provided in later chapters. In chapter 6 the constructed ray files are used to simulate the illuminance distributions in a sidelighted space, and the obtained illuminance levels are compared to results obtained from the software Radiance. In chapter 9, the luminous intensity distributions of different daylight scenes are presented, and these distributions can be used in a qualitative validation of the ray files. Finally, in chapter 10 the average window luminance is calculated using the TracePro ray files, and the results are again validated by a comparison with sky luminance values that are obtained analytically.

6 Illuminance distributions in a sidelighted space

I was born on the prairies where the wind blew free and there was nothing to break the light of the sun. I was born where there were no enclosures.

Geronimo

6.1 Introduction

As discussed earlier, several factors can influence the light distribution in an architectural space. This includes the geometry of the space and of daylight openings, as well as the optical properties of the interior surfaces. In the evaluation of daylighting systems, it can be useful to apply evaluation methods that are independent of the architectural space in which they are applied. However, in order to obtain a basis for qualifying such evaluation methods it is still beneficial to define an architectural space that can function as a reference space.

In chapter 5 it was described how mathematical models representing the daylight source were implemented as ray files into the TracePro software. In this chapter the same ray files are used to obtain the illuminance distributions of daylight in a narrow sidelighted space with an upper and a lower window opening.

A TracePro model of the sidelighted space is constructed, and this space is used to validate the 10 different ray files described in chapter 5.

The sidelighted space is also used to illustrate the importance of the reflectance values of the interiors; for the daylight quantity as well as for the distribution of daylight within the interiors.

6.2 Description of a sidelighted space

The reference space constructed is a rectangular space, 3.0 m high, 4.0 m wide and 7.0 m deep. The window openings are positioned on one of the short walls. There are two window openings, an upper daylight opening and a lower view opening. Both window openings are 3.0 m wide and centrally positioned, leaving half a meter of wall on each side. The upper window opening is half a meter high, starting at a height of 2.0 meters. The lower window opening is one meter high, starting at a height of 0.9 meters. The wall area of the window wall is 12.0 m^2, and the floor area is 28.0 m^2. The total window area is 4.5 m^2. This gives a window-to-wall ratio of 0.375 and a window-to-floor ratio of 0.161. For simplicity, there are no window sills, and all of the walls are modelled as two-dimensional thin sheets.

As can be seen from Figure 6-1, the reference space is rather narrow. The relatively large depth of 7 m is chosen so as to be able to study the effect of daylight redirection systems that are aimed at guiding daylight towards the deeper interiors of the space.

The location of the window openings are chosen so as to represent a typical situation for an office space with a lower view window and a smaller daylight opening located above eye height. During the forthcoming simulations it is possible to apply different blind types and slat angles separately in the two windows.

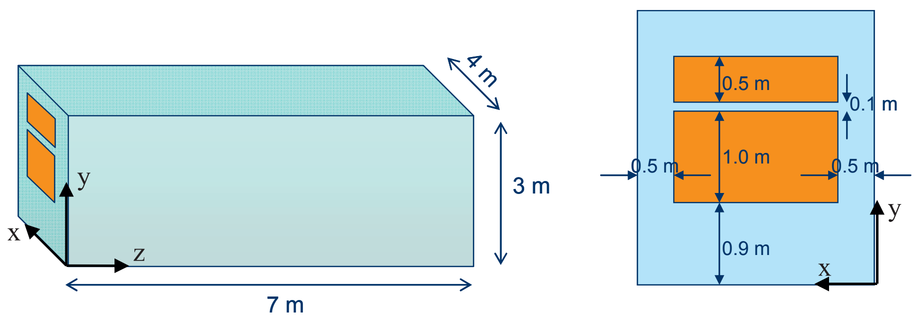


Figure 6-1 Reference space for daylight simulations. The dimension of the space is shown to the left, and a front view of the facade wall with the location of the window openings is shown to the right.

6.2.1 Coordinate system

The coordinate system for the reference space is the same as that shown in Figure 4-6. This means that the window facade lies in the xy-plane, and light from the outside, passing through the window openings and into the interiors will propagate in the general direction of the positive z-axis. This is also the convention that is recommended and generally used for ray tracing with TracePro. Note that some sources use a different coordinate system for daylighting systems, where the z-axis is pointing in the opposite direction, towards the exterior.

6.2.2 Ray tracing specifications

For the sidelighted space, separate TracePro source files are developed to be used for both the view window and the daylight opening. For the daylight opening

30 000 rays are used for diffuse skylight and 30 000 rays are used for direct sunlight, adding up to a total of 60 000 rays (except for scene 1). For the view window the numbers are doubled; 60 000 rays are used for diffuse skylight and 60 000 rays are used for direct sunlight, adding up to a total of 120 000 rays.

In order to limit the number of rays accounted for in a TracePro simulation, rays are terminated when the flux reaches a certain threshold value as compared to the starting flux of the original incident ray. For the simulations presented here and in the following, the threshold level was set to 1% of the starting flux of each ray. This means that multiple reflections (and scattering) occurring, for example within the interiors of the space, are accounted for as long as the resulting ray flux is more than 1% of the starting flux.

6.3 Floor illuminance from overcast sky

As a first example the overcast sky scene (S1) is applied to the reference space with window openings containing no glazing or daylighting components (void).

The illuminance levels on any surface can easily be found following from a ray trace. It is also possible in TracePro to extract the illuminance levels on a “virtual” surface, such as, for example, a surface representing the work plane; typically located 0.85 m above the floor level. Unfortunately, for the current version of TracePro, the process of obtaining the illuminance levels on a “virtual” plane is rather cumbersome. It was therefore decided to analyse the illuminance levels on the “real” surfaces instead.

As expected, the illuminance values on the floor plane obtained from the TracePro ray trace are highest near the window (above 1000 lux) and decreases towards the back wall (to less than 100 lux). In Figure 6-2 an illuminance map of the floor generated by the TracePro software is shown. The irregular pattern is caused by the limited number of traced rays (30 000 incident rays). As noted earlier, the number of rays in the ray files representing the different daylight scenes is chosen in order to reduce simulation time.

The floor area covers the region enclosed by a dotted line (from 0 mm to 4000 mm in the x-direction, and from 0 mm to 7000 mm in the z-direction). The window facade is located at z = 0 mm and the back wall at z = 7000 mm**.** The illuminance map given in Figure 6-2 is obtained by assuming that all interior surfaces are completely black (reflectance values of 0% for floor, walls and ceiling).

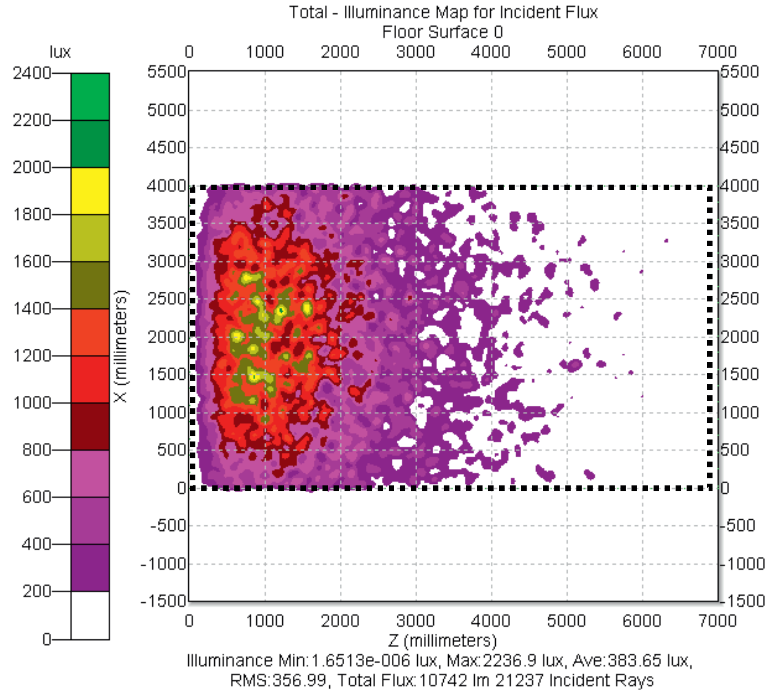


Figure 6-2 Illuminance map of the floor area created by the TracePro software. The data is generated for overcast sky conditions (S1) with black interior surfaces.

The ray trace data obtained from TracePro can be copied into other data programs, such as a spreadsheet. This is convenient for data analysis and graphical illustrations.

In Figure 6-3 the average illuminance on the floor as a function of the distance from the window wall is shown. The values are obtained under overcast conditions (S1) with no glazing or daylighting components present in the window openings. All interior surfaces are black (ρ = 0).

The given illuminance for each room depth is an average value obtained by calculating the arithmetic mean of values over the width of the floor. The maximum illuminance of the floor (averaged along the x-direction) is about 1200 lux, obtained at a distance of approximately 1 m from the window wall. In the inner zone near the back wall the (averaged) floor illuminance drops to less than 100 lux.

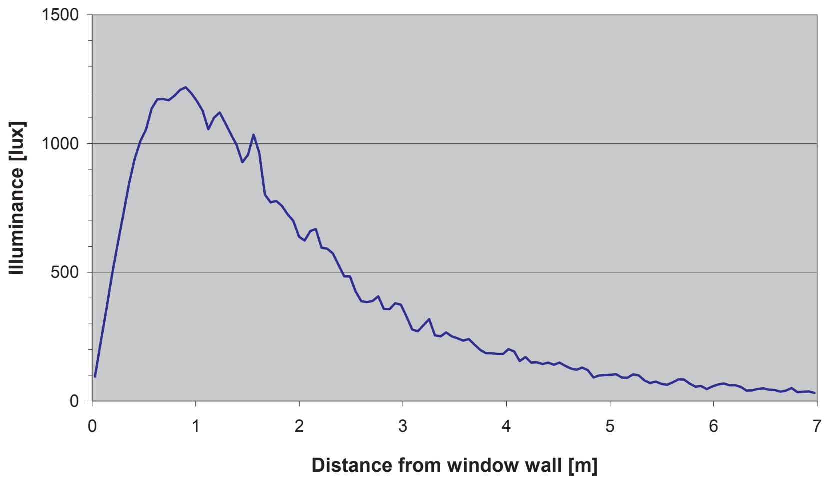


Figure 6-3 Average illuminance on the floor as a function of the distance from the window wall under overcast sky conditions (S1). No glazing or daylighting components are present in the window openings and all the interior surfaces are black (ρ = 0).

6.4 Validation of illuminance distributions

The main aim of this section is to provide further validation of the ray files constructed for TracePro and representing the 10 daylight scenes discussed in chapter 5. The ray files are used to illuminate the sidelighted space described above, and the resulting illuminance distributions are compared to those obtained with the software Radiance. Please note that all the Radiance simulations presented here were carried out by Dr. Matthias Haase at NTNU.

For the validation, two special conditions are used:

1. the interior surfaces of the room are completely black, with reflectance values of 0%.
2. the window openings are free from any glazing components.

Black interior surfaces are used in order to remove internally reflected light in the simulations. Any discrepancies between TracePro and Radiance with respect to the handling of internally reflected light are thereby eliminated.

The reason for not using any glazing in the window openings is in order to eliminate the effects of the glazing materials. Any discrepancies between TracePro and Radiance with respect to glazing properties are thereby eliminated.

6.4.1 Ground illuminance

As shown in chapter 5, there are many different mathematical models for the diffuse skylight as well as for the intensity of the direct sunlight. The different mathematical models provide results that might differ substantially.

It is not clear from the Radiance manual (Larson and Shakespeare 1998) exactly which mathematical models are used to calculate the zenith luminance of the clear sky and overcast sky, or the intensity of the direct sunlight at different solar elevations. For this reason it is useful to compare the ground illuminance obtained in TracePro and in Radiance. This can be used to facilitate the comparison between the resulting illuminance distributions within the interiors of a space.

The ground illuminances of the 10 scenes obtained from TracePro and Radiance are given in Table 6-1. For TracePro, both the diffuse and direct components to the ground illuminances are shown. The last column show the relative difference in ground illuminances obtained with TracePro and Radiance.

The results show that the ground illuminances obtained with TracePro are from 12% to 47% higher than those obtained with Radiance. This is not really surprising considering the large differences in the different mathematical models of skylight and sunlight discussed in chapter 5. In particular, the results indicate that the equations used to calculate direct sunlight are different in TracePro and Radiance.

Table 6-1 Ground illuminances for 10 daylight scenes from TracePro and from Radiance.

Scene	Sky type	TracePro			Radiance	Difference
		E_{diff} [lux]	E_{dir} [lux]	E_{ground} [lux]	E_{ground} [lux]	E_{TP} / E_{RAD}
1	overcast	10 807	0	10 807	9660	1.12
2, 3, 4	low sun	5 083	7 135	12 218	8369	1.47
5, 6, 7	int. sun	12 725	43 571	56 296	42306	1.33
8, 9, 10	high sun	16 210	76 703	92 913	66406	1.40

6.4.2 Floor illuminance

The floor illuminance of the sidelighted space described above is obtained for the 10 daylight scenes from simulations in TracePro and in Radiance. The results are shown in the following 10 figures. Since many of the daylight scenes include direct sunlight, the illuminance values are plotted on a logarithmic scale.

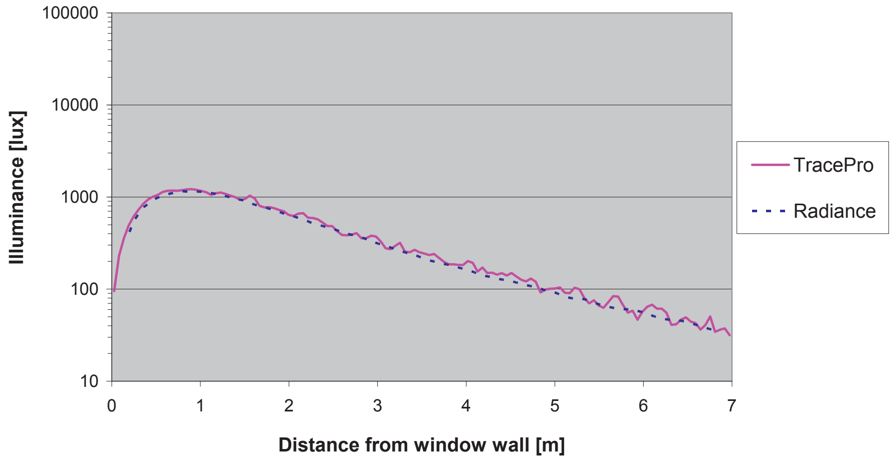


Figure 6-4 Floor illuminance for overcast sky (S1).

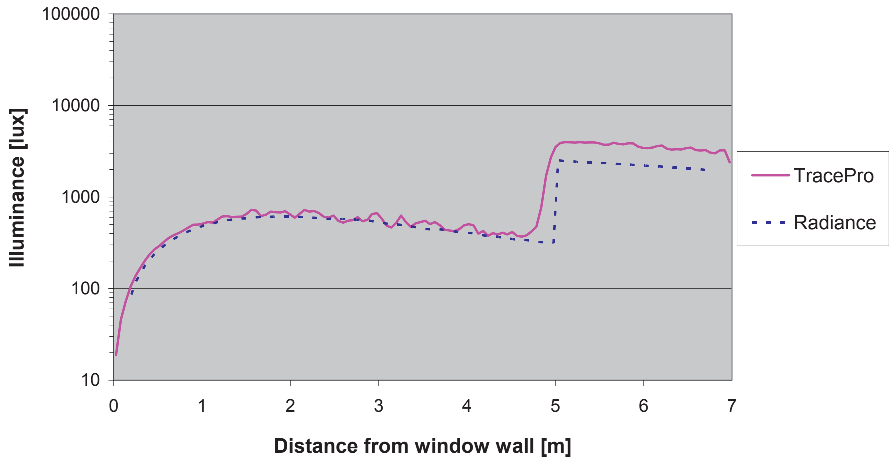


Figure 6-5 Floor illuminance for low sun (S2).

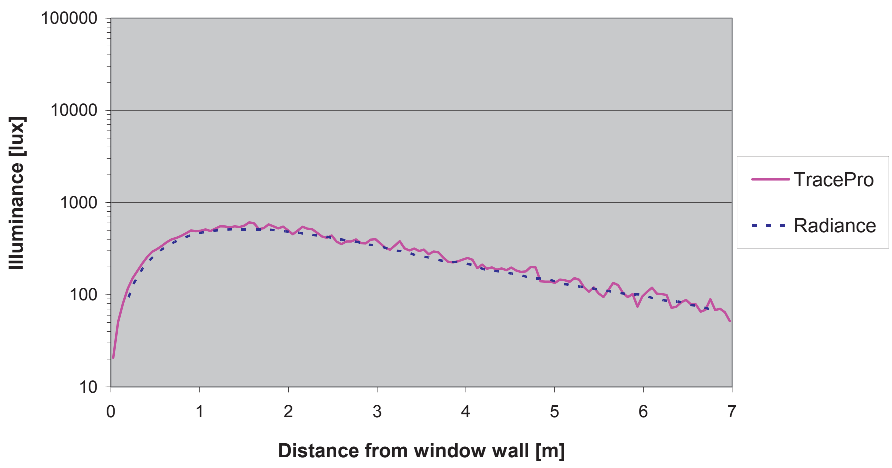


Figure 6-6 Floor illuminance for low sun (S3).

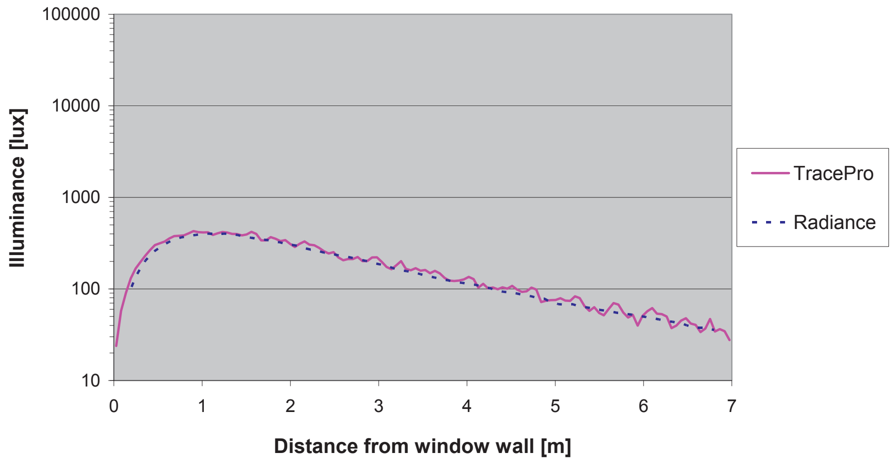


Figure 7-7 Floor illuminance for low sun (S4).

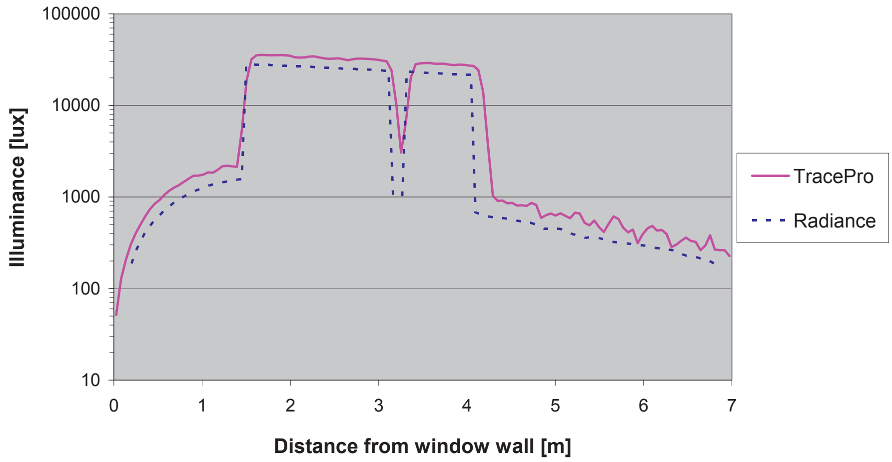


Figure 6-8 Floor illuminance for intermediate sun (S5).

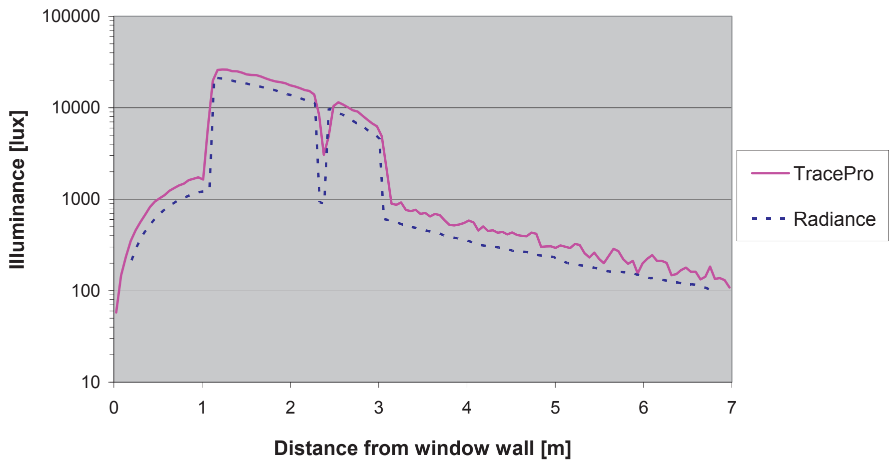


Figure 6-9 Floor illuminance for intermediate sun (S6).

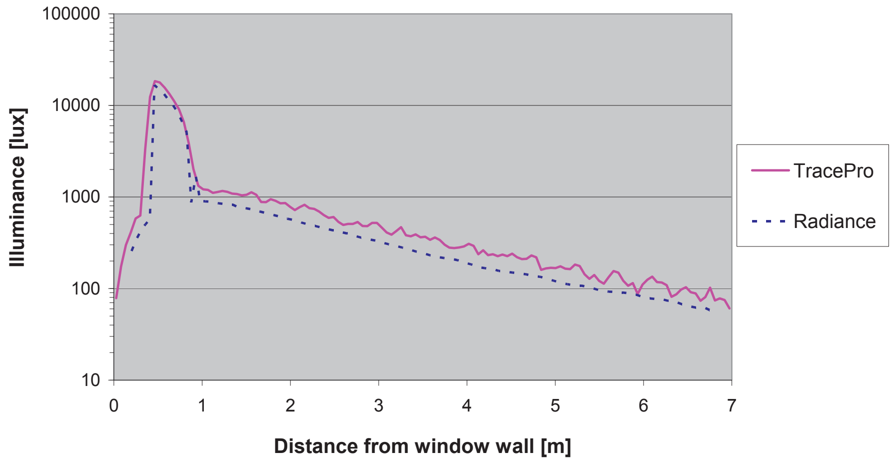


Figure 6-10 Floor illuminance for intermediate sun (S7).

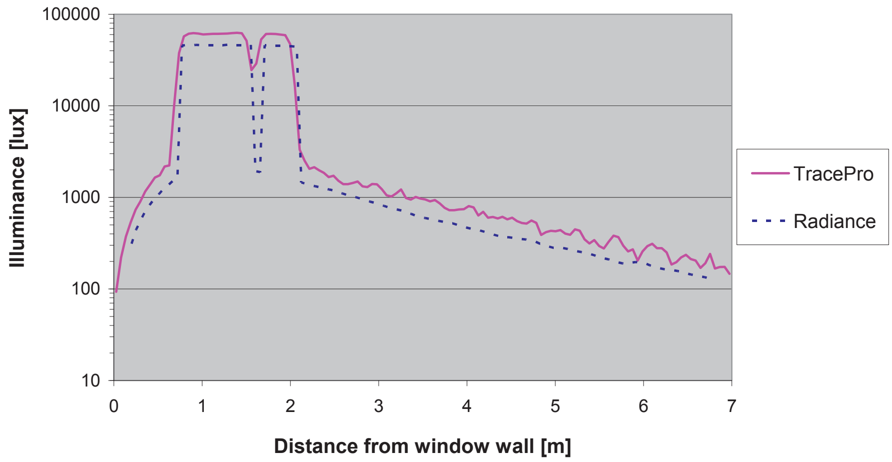


Figure 6-11 Floor illuminance for high sun (S8).

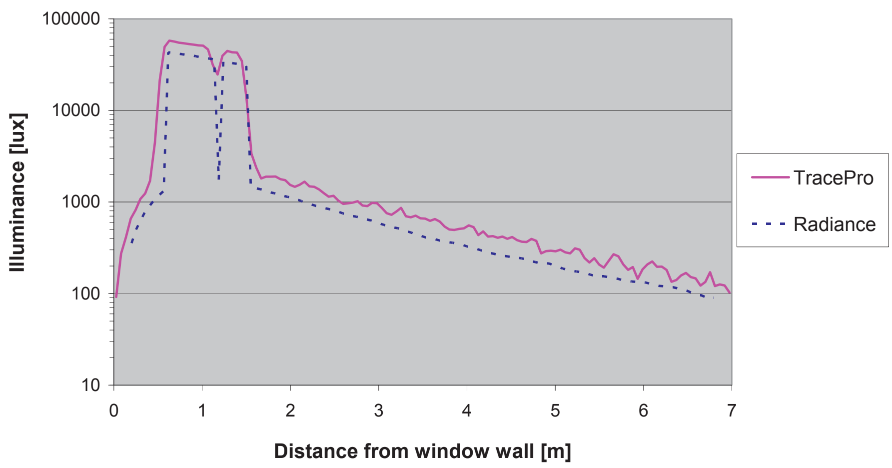


Figure 6-12 Floor illuminance for high sun (S9).

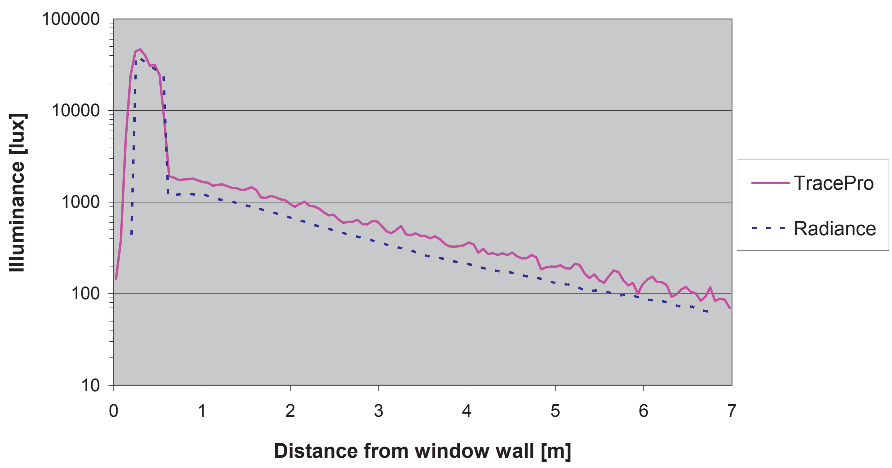


Figure 6-13 Floor illuminance for high sun (S10).

6.4.3 Overcast sky

The results provided in Figure 6-4 show that there is a very good agreement between the results from TracePro and Radiance. The ground illuminance obtained from TracePro is 12% higher than that obtained from Radiance. If we adjust for this difference, the values from TracePro and Radiance are practically identical. This validates that, although the absolute levels are slightly different, the *distribution* of the light is identical. This result is as could be expected, since both the TracePro ray files and the results from Radiance are based on the equation for the CIE Traditional Overcast Sky (equation 5.3).

The results for overcast sky validate the TracePro ray file that is used for scene 1.

6.4.4 Low sun

The results provided in Figure 6-5, Figure 6-6 and Figure 6-7 show the floor illuminance for the low sun scenes.

For scenes 3 and 4 (S3 and S4) only the diffuse skylight is incident on the floor, as all direct sunlight hits the side wall of the space. For scene 2 (S2) the inner parts of the floor is also illuminated by direct sunlight.

For the floor area that is illuminated by light from the clear sky, the results from TracePro and Radiance are again very similar.

However, for the floor area that is directly illuminated by the sun, TracePro gives higher illuminance values than Radiance. The difference here is close to 47%, the same difference as for the ground illuminance. This indicates that, for low sun, the *level and distribution* of the light from the clear sky is very similar in TracePro and Radiance, while the level of direct sunlight is higher in TracePro.

However, the aim here is not to validate the *absolute* light levels but rather the light *distributions.* In this respect the results provided can be considered as a satisfactory validation of the TracePro ray files for the low sun scenes 2, 3 and 4.

6.4.5 Intermediate sun

The results provided in Figure 6-8, Figure 6-9 and Figure 6-10 show the floor illuminance for the intermediate sun scenes. For these scenes the ground illuminance obtained from TracePro is 33% higher than that obtained from Radiance. By correcting for this difference, the values from TracePro and Radiance provide a very good match.

This indicates that for the intermediate sun scenes the levels for both direct sunlight as well as diffuse skylight are higher in TracePro. However, again, the *distribution* of light seems to be very similar.

Another difference between the two simulation results is that the TracePro simulation does not provide the same spatial accuracy. The dips in illuminance levels between the two patches of direct sunlight (from the two window openings) seen for scenes 5 and 6 are too small in the TracePro simulations. This is a defect caused by the spatial smoothing. If needed, the spatial accuracy of TracePro could be improved by tracing more rays and by reducing the spatial smoothing.

Apart from this difference the light distributions are very similar and the results can be considered as a satisfactory validation of the TracePro ray files that are used for intermediate sun scenes 5, 6 and 7.

6.4.6 High sun

The results provided in Figure 6-11, Figure 6-12 and Figure 6-13 show the floor illuminance for the high sun scenes.

The results follow the same pattern as for the intermediate sun scenes. The light *distributions* from TracePro and Radiance are very similar, but the absolute levels are higher in TracePro; both for diffuse skylight and for direct sunlight.

Again, if we adjust for the difference in ground illuminance (40% higher with TracePro), the obtained results are very similar.

The results can therefore be considered as a satisfactory validation of the TracePro ray files that are used for high sun scenes 8, 9 and 10.

6.5 Components of interior illuminance

In this section the emphasis is placed on the components that contribute to the interior illuminance. As shown in the following, the interior reflectance values in a space are of great importance for the resulting illuminance distributions.

6.5.1 Four components of interior illuminance

The illuminance at a given location within the interiors can be considered as a sum of four different components:

- (i) the direct sunlight component
- (ii) the diffuse skylight component
- (iii) the ground reflected (or externally reflected) component
- (iv) the internally reflected component (IRC)

It should be noted that the first two of these components are often combined and described as the “direct component”. In the following, the direct component (DC) refers to the combination of (i) and (ii).

The direct sunlight component (i) is the illuminance component that originates from direct sunlight. The direct sunlight component will vary strongly depending on whether or not the sun is “seen” from a given location within the interiors.

Similarly, the diffuse skylight component (ii) to the illuminance will vary according to how much of the sky that is visible at the given interior location. The diffuse skylight component of a sidelighted space illuminated from an overcast sky will typically be highest on locations below the windows and relatively near the window wall.

The ground reflected component (iii) to the illuminance is the contribution to the illuminance that originates from exterior surroundings (including the ground, nearby buildings, etc.) The ground reflected component will depend on the reflectance properties of exterior surroundings, and on how much of the exterior surroundings that are visible at the given interior location. For sidelighted spaces, the ground reflected component will typically be highest on interior locations located above the windows and near the window wall.

The internally reflected component (iv) is of great significance, especially when daylight redirection systems are applied. As will be seen in the next sections, the internally reflected component (IRC) depends strongly on the reflectance properties of the interior surfaces. For sidelighted spaces the internally reflected components typically decreases with the distance from the window wall.

It is possible to extract illuminance data for the internally reflected component (IRC) from the TracePro simulation results. By first setting the reflectance values of all the interior surfaces to 0%, the direct plus externally reflected components can be found. These values can be subtracted from the values that include the IRC.

The IRC for the reference space in overcast sky conditions (S1) as obtained by this approach is given in Figure 6-14. It can be seen, as expected, that the illuminance originating from interior surfaces (IRC) decreases towards the back wall. However, the decrease towards the back wall is in this example much larger for the direct component (DC).

The reflectance values used for floor, walls and ceiling are here 20%, 50% and 70% respectively.

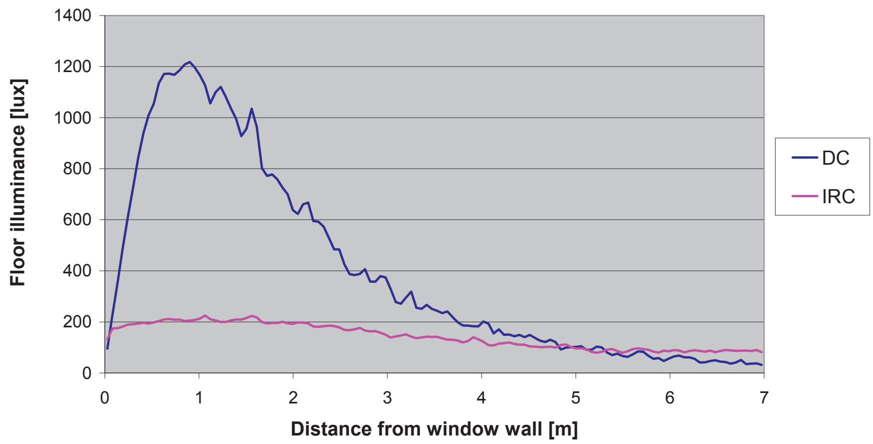


Figure 6-14 The internally reflected component (IRC) and direct component (DC) of floor illuminance for the reference space under overcast sky conditions (S1). No glazing or daylighting components are present in the window openings.

6.5.2 The internally reflected component

In this section a closer look at the IRC is presented. Depending on the reflectance properties of the interior surfaces, the IRC can contribute significantly to the interior illuminance. In the following it is shown that high reflectance values for the interior surfaces are important in order to obtain high average illuminance levels, as well as to obtain a more uniform distribution of the daylight within an interior space.

Hopkinson (1966) gave a method to estimate the IRC based on the theory of the integrating sphere. According to this method the average illuminance on all of the interior surfaces resulting from the IRC can be found from:

$$E_{IRC\_avg} = \frac{\text{First reflected flux from interior surfaces}}{\text{Total area of interior surfaces} \cdot \left(1 - \rho_{avg}\right)} \tag{6.1}$$

The average reflectance (ρ_{avg}) of the interior surfaces includes the window area and is found from:

$$\rho_{avg} = \frac{\rho_{floor} \cdot A_{floor} + \rho_{walls} \cdot A_{walls} + \rho_{ceiling} \cdot A_{ceiling} + \rho_{win} \cdot A_{win}}{A_{total}} \tag{6.2}$$

It is noted by Hopkinson that this formula for calculating IRC applies to a sphere with idealised diffuse surfaces. Hopkinson presents empirical adjustments to the formula to bring it into line with actual measurements in a wide variety of rooms. According to Hopkinson, the crux of the problem lies in determining the first reflected flux from the interior surfaces of the room to a sufficient order of accuracy.

In the TracePro model with overcast sky discussed above, the incident flux through the window opening equals 23.782 lm (5285 lux from Table 5-3 times 4.5 m^2), and the total area of the interior surfaces (including the window area) is 122 m^2. Under the condition that all interior surfaces (apart from the window opening) have the same reflectance (ρ_{int}), the first reflected flux is easily calculated and is equal to incident flux multiplied by this reflectance. For the reference room under overcast sky conditions the average illuminance can therefore be estimated to:

$$E_{IRC\_avg} = \frac{23\,782 \cdot \rho_{\text{int}}}{122 \cdot \left(1 - \rho_{avg}\right)} \tag{6.3}$$

It is of interest to compare this approximation with results obtained from TracePro simulations when the reflectance values of the interior surfaces of the room are varied.

In Figure 6-15 the average illuminance from the IRC over all interior surfaces in the reference room is given for different average reflectance values. The lines indicate results obtained when all interior surfaces (except the window opening) have the same reflectance (ρ_{int}). The TracePro calculations were carried out with reflectance values of 20%, 40%, 60%, 80% and 100% respectively. The corresponding average reflectance value presented below is slightly lower than these values because the (unglazed) window opening has a reflectance of zero.

The results show a near perfect agreement between the TracePro simulations and the calculations based on the Hopkinson method. For the case of 100% reflectance the TracePro simulations initially gave a much lower value. It was found that this was mainly due to the intercept limits for rays used in the simulations. By increasing the number of allowed intercepts from 50 to 200 the results from the simulations increased and approached the calculated values, as shown in Figure 6-15. This indicates that for very high interior reflectance values (close to 100%) a significant portion of the incident light will bounce back and forth more than 50 times before exiting out through the window opening. This also explains the rapidly increasing levels of the IRC as the interior reflectance values approaches 100%.

In a typical room the reflectance of the floor is lower than the reflectance of walls and ceiling. Commonly used values for floor, walls and ceiling are 20%, 50% and 70% respectively. To represent a space with high reflectance values the numbers 50%, 70% and 90% for floor, walls and ceiling could be applied. The corresponding average reflectance values (ρ_{avg}) are found from equation 6.2.

Again it is possible to calculate the average illuminance from equation 6.1 (the Hopkinson method). The total first reflected flux (Φ_{FR_tot}) can now be obtained from the following equation:

$$\Phi_{FR\_tot} = \Phi_{floor} \cdot \rho_{floor} + \Phi_{walls} \cdot \rho_{walls} + \Phi_{ceiling} \cdot \rho_{ceiling} \qquad (6.4)$$

Here, Φ_{floor}, $\Phi_{walls\ and}$ $\Phi_{ceiling}$ are the first incident flux on the floor, walls and ceiling respectively. These values can be obtained from TracePro calculations (by setting the reflectance of all the interior surfaces to zero). For the reference room under overcast sky conditions the first incident flux is given in Table 6-2.

Table 6-2 First incident flux from overcast sky (S1).

	First incident flux [lm]
Floor	11 199
Walls	9 968
Ceiling	2 745

These two situations of standard and high room reflectance have also been implemented into the TracePro model. The average illuminance is then obtained directly from TracePro simulations.

Results from calculation based on the Hopkinson method as well as the TracePro simulations are both plotted in Figure 6-15. Again, the results from the calculations based on Hopkinson and the TracePro simulations are very similar.

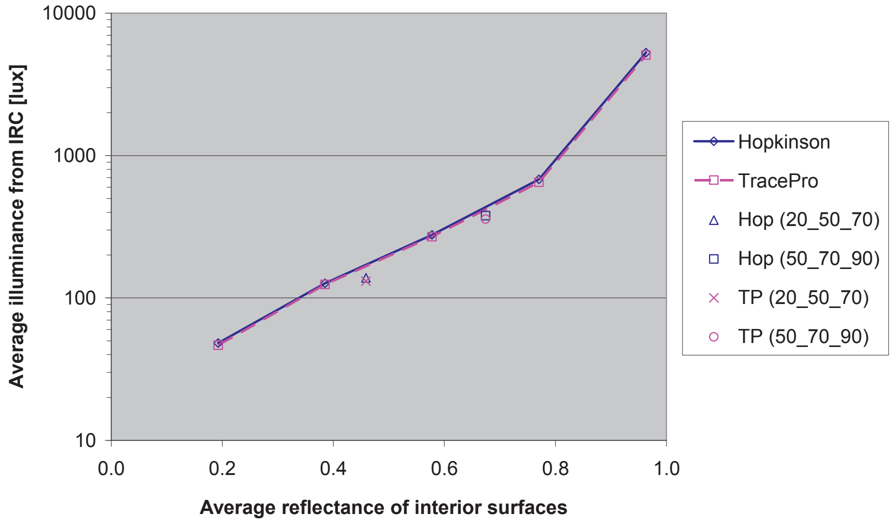


Figure 6-15 Average illuminance from IRC over all interior surfaces in the reference room under overcast sky conditions as a function of average reflectance from all surfaces (assuming diffuse reflectance). A logarithmic scale is applied to the y-axis.

In Figure 6-16 the same results are plotted with a linear vertical axis. As can be seen, the average illuminance from the IRC is slightly lower for the two more realistic situations compared to the results obtained when all surfaces have the same reflectance.

This can be explained by the fact that most of the incident light is directed towards the floor region, and little towards the ceiling. Since the reflectance of the floor (and walls) is lower than the ceiling, this results in a lower first reflected flux, compared to the situation with the same reflectance on all surfaces.

The opposite effect would be true when daylight redirection systems that redirect most of the incident flux towards the ceiling are applied. In this case it is beneficial to have the highest reflectance on the ceiling, as this would increase the first reflected flux.

Looking at the results it is quite interesting to observe that the internally reflected component to the average illuminance increases from about 135 lux for the standard reflectance values to about 370 lux for the high reflectance values; a significant increase!

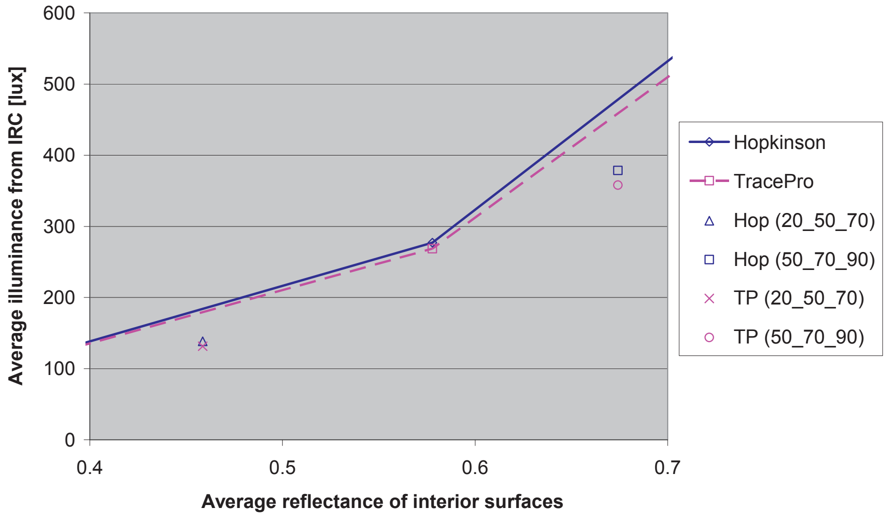


Figure 6-16 Average illuminance from IRC under overcast sky. A linear scale is applied to the y-axis.

6.5.3 Uniformity of the IRC

The internally reflected component (IRC) affects not only the levels of the illuminance but also the uniformity of the illuminance in a space. With high reflectance values the light bounces back and forth and produces a more even distribution within the interiors. For the narrow sidelighted space under consideration, the average illuminance of the back wall to that of the window wall under overcast sky conditions can be used to indicate the uniformity (U) of the illuminance levels.

$$U = \frac{E_{back\,wall}}{E_{window\,wall}} \tag{6.5}$$

The uniformity levels obtained by this approach are presented in Figure 6-17. The results show that the uniformity approaches 1 as the interior reflectance values increases towards 1. This is an important result in that it shows that high interior reflectance values can contribute substantially to more uniform lighting levels and thus also to enhanced utilisation of daylight in buildings.

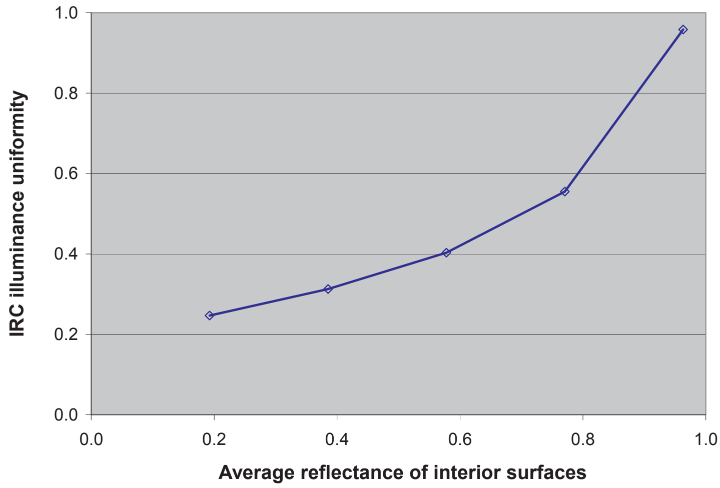


Figure 6-17 Uniformity of illuminance as a function of interior reflectance values. The values are obtained using the ray files constructed to represent overcast sky conditions (S1).

For a space with interior reflectance values approaching 1, the need for redirecting daylight towards the deeper interiors of the space diminishes. In practice however, the reflectance values are not so high as to produce uniform lighting conditions without daylight redirection. In the next section some further examples are provided in order to illustrate the importance of the interior reflectance values.

6.5.4 Examples with different interior reflectance

The ray files representing overcast sky conditions (S1) have been used to predict the floor illuminance in the reference space for different reflectance values of the interior surfaces. In one example the case of "very low interior reflectance" is illustrated. Here, all reflectance values are set to 20%. In another example all reflectance values are set to 90% to illustrate the effect of "very high interior reflectance". In between these two cases lies the "standard" case where the reflectance's of floor, walls and ceiling are set to 20%, 50% and 70% respectively, as well as a more realistic "high interior reflectance" case where the reflectance values are set to 50%, 70% and 90%. The simulation results are illustrated in Figure 6-18.

As expected, the case where all values are set to 20% provides the lowest illuminance values. The improvement when wall and ceiling reflectances are increased to 50% and 70% respectively is not very large. Providing the space with high reflective surfaces (50%, 70% and 90% for floor, walls and ceiling) gives a significant increase in illuminance values, especially in the innermost parts of the space.

As could be expected, the case where all surface reflectances are set to 90% provides the highest illuminance values. In this case the relative decrease in illuminance with distance from the window wall is much smaller. Thus, as concluded before, these high reflectance values not only provide high illuminance levels but also a more uniform distribution of the illuminance levels from daylight.

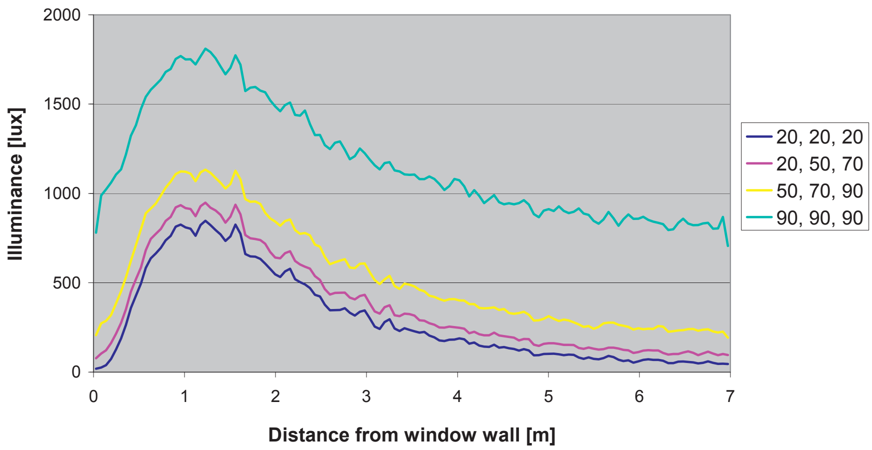


Figure 6-18 Average illuminance on the floor for different interior reflectance values (on floor, walls and ceiling) as a function of the distance from the window wall for the reference room under overcast sky conditions (S1). Double glazing is present in the window openings.

6.6 Summary and conclusions

In this chapter a narrow sidelighted space was introduced. This space was used first and foremost to validate the TracePro ray files discussed in chapter 5. The validation was carried out mainly be comparing the floor illuminance values obtained from the TracePro ray files with floor illuminance values obtained from the software Radiance.

The results obtained from TracePro agreed well with those obtained from Radiance, and especially so when the results were adjusted for differences in ground illuminance. The results presented in this chapter provide a strong argument for the correctness of the TracePro ray files, but also indicates that the mathematical equations that form a basis for the TracePro ray files are not exactly the same as those used in the Radiance software.

In this chapter it was also shown that the reflectance values of the interior surfaces play a significant role in determining the resulting interior illuminance levels, including the *uniformity* of the illuminance. The results from the TracePro simulations were compared to theoretical results based on the findings of Hopkinson. Again, a very good agreement was found, and this result serves to validate that TracePro simulations of the reference space, with different reflectance values applied to the interior surfaces, produce correct results for interior illuminance levels.

7 Illuminance distributions for different venetian blind configurations

There are two ways of spreading light: to be the candle or the mirror that reflects it.

Edith Wharton

7.1 Introduction

In the previous chapter a sidelighted reference space was introduced, and the importance of the interior reflectance values was investigated. In this chapter the same space is applied in order to generate illuminance distributions on the floor and ceiling, resulting from various venetian blind configurations in the upper and lower window openings of the space.

The main aim is to obtain a better understanding of how a daylight redirecting blind compares to a traditional white venetian blind with respect to interior illuminance levels, and also to investigate the effect of different modes of operation of the blinds, expressed through different blind tilts.

Illuminance levels for both the floor and the ceiling of the reference space are investigated in this chapter.

Redirection of daylight towards the ceiling is beneficial for several reasons; in this way the uniformity of the illuminance distribution within the interiors is improved, contrasts are reduced and the room appears less gloomy. The illuminance levels from daylight in the ceiling are important also with respect to potential energy savings in electric lighting. Today, many electric lighting installations in offices uses indirect lighting (via the ceiling) in order to provide satisfactory lighting conditions. It can be argued that daylight redirection systems are particularly useful and efficient with respect to reducing the need for indirect electric lighting.

7.2 Specification of simulation conditions

As illustrated in the previous chapter, the reflectance values of the interior surfaces of a space play a vital role in determining the resulting illuminance distribution.

However, not all reflectance values are feasible in practice. The “standard” values of 20%, 50% and 70% on floor, walls and ceiling are the most often used in simulations because experience has shown these to be realistic values, at least for office buildings. In the following these values will be used as standard and can be assumed to apply unless other values are explicitly stated.

It is clear from earlier sections that both the geometrical properties and the optical properties of the blinds will affect the illuminance distribution. In the following examples, the geometrical and optical properties are standardised as follows:

A “white blind” (w) indicates a blind with a diffuse reflectance of 70% on both sides of the blind slats and a spacing to width ratio (*S/W*) of 0.9 and. The blind slats are modelled as flat sheets with a thickness of zero. The blind tilt is specified by the tilt angle (β). As an example; w45º indicates a (white) blind with *S/W* of 0.9 and with a diffuse reflectance of 70%, tilted 45º.

The reflectance of 70% is typical for white blinds, although it is slightly lower than the white blinds shown in Figure 3-3 and Figure 3-4.

A “reflective blind” (r) indicates a blind with slats where the upper side of the slats have a specular reflectance of 95% while the lower side has a diffuse reflectance of 40% (grey). The reflective blinds have a spacing to width ratio (*S/W*) of 0.6, with flat slats with a thickness of zero. As an example; r0º indicates a reflective blind as described above that is tilted 0º (untilted).

For the reflective blind it is here assumed that a high quality reflector material is used on the reflective side. Today, reflector materials with a reflectance of 95% (or more) are commercially available and commonly used in electric lighting luminaries. On the lower side of the slats a grey surface is assumed. The use of a grey lower side is common for daylight redirecting blinds, in order to reduce glare from (double) specular reflections.

These two “standardised conditions” are chosen in order to limit the number of blind properties simulated while at the same time representing realistic conditions.

For all simulation configurations that follow in this chapter, the presence of a double glazing is included in the TracePro models. The window panes are modelled as non-absorbing with a refractive index (n) of 1.52.

7.3 Modes of operation for venetian blinds

The appropriate tilting angle of the blinds depends on what is mostly desired with respect to several different and sometimes contradicting factors. Blinds can be tilted so as to reduce overheating, to prevent discomfort glare, to enhance viewing potential in certain directions or to increase the amount of daylight within the interiors.

In the following sections both the “reflective blind” and the “white blind”, as specified above, is considered. The blinds are tilted (or raised) according to the following modes of operation:

- no blinds (or raised blinds)
- closed blinds
- semi-closed blinds
- open blinds

7.3.1 No blinds (NB)

In order to enhance the view out of the window or to admit more daylight the blinds can be completely raised. Simulation results for this situation are carried out by modelling the double glazing unit only (without the presence of blinds).

7.3.2 Closed blinds (CB)

In order to darken the interiors as much as possible, to reduce the solar heat gains through the window opening, or eliminate any sources of glare, the blinds can be titled to the closed position. In the simulations presented in this chapter the closed blinds are assumed to be 100% closed and thus admitting no daylight between the slats. It should be noted that such a configuration is not really possible in practice (for most blinds), and the results for this situation should therefore be considered as a theoretical limit for an ideal blind.

7.3.3 Semi-closed blinds

The blinds can also be tilted to a semi-closed position. This mode of operation can be relevant in order to avoid glare or overheating, while still admitting some daylight to the interiors and also providing a limited view (especially towards the ground). It is also relevant for situations when building occupants have neglected to adjust the blinds after prior sunlight conditions requiring glare protection or overheating protection.

In this chapter only the white blind will be investigated in the semi-closed position, and the tilt angle representing this position is chosen as 45º. The semi-closed position with a white blind tilted at $\beta = 45º$ is only considered in situations where this tilt angle stops all direct sunlight from passing through the blinds.

In later chapters also the reflective (daylight redirecting) blind will be considered in the semi-closed position. For the reflective blind, as a result of the lower spacing to width ratio (S/W = 0.6), the tilt angle representing the semi-closed position is chosen as 30º.

7.3.4 Open blinds

The open blind position is the most complex to define, as the tilt angle will here depend on the position of the sun. The main reasons for applying the open blind positions are to admit as much daylight as possible to the interiors and also to enhance outward viewing potential. At the same time it is considered imperative that direct sunlight is not allowed to enter between the blind slats.

For the reflective blinds, the tilt angles are chosen so as to:

i) stop direct sunlight from passing through the blinds.
ii) avoid specular reflections (from the upper slat surface) in a downward direction.
iii) redirect daylight towards the deeper interiors, when possible.

For the white blinds, the tilt angles are chosen so as to:

i) stop direct sunlight from passing through the blinds.
ii) enhance horizontal viewing, when possible.

7.4 Specification of tilt angles

The modes of operation outlined in the previous section give the tilt angles specified in Table 7-1. Note that the daylight scenes are here ordered according to ascending projected solar elevation. A more detailed explanation for the respective tilt angles considered is provided for each daylight scene in the following sections.

Table 7-1 Blind tilt angles for different blind types and control strategies.

Scene	Projected solar elevation	Blind tilt angle		
		Open blind		Semi-closed blind
		Reflective blind	White blind	White blind (45°)
1	-	0.0°	0.0°	45.0°
2	10.3°	26.8°	53.0°	-
3	14.0°	22.6°	47.8°	-
5	30.9°	1.1°	20.7°	45.0°
4	34.3°	-3.5°	14.8.0°	45.0°
6	39.2°	-10.5°	6.0°	45.0°
8	51.0°	-20.0°	0.0°	45.0°
9	59.3°	-25.0°	0.0°	45.0°
7	65.9°	-30.0°	0.0°	45.0°
10	77.7°	-35.0°	0.0°	45.0°

7.5 Results for overcast sky

The illuminance distribution on the floor in a sidelighted space in the situation with only a double glazing (no blinds) in the window opening was shown in section 6.5.4. In the present section interior venetian blinds will be introduced in the window openings, and their effect on the illuminance distribution will be discussed.

Several different blind configurations are simulated:

As a base case, the situation without any blinds (NB) is considered. Furthermore, open blinds are relevant under overcast sky conditions as a means to reduce glare while keeping a relatively good horizontal view. For overcast sky conditions, since there is no direct sunlight, open blinds will correspond to blinds with untilted slats. Finally semi-closed white blinds (tilted 45º) are included in the simulation. This could be relevant when further glare protection is required, or perhaps more relevant, when the occupants have neglected to adjust the blinds after prior sunlight conditions.

7.5.1 Floor illuminance

Several different combinations of blind type and tilt angle are simulated and the resulting average floor illuminance values are illustrated in Figure 7-1. In this and the following figures, the first term refers to the blind configuration in the view opening, while the second term refers to the blind configuration in the daylight opening.

The results show that the highest illuminance values are obtained when no blinds are present in both the view opening and the daylight opening (NB + NB).

However, introducing an untilted reflective blind in the daylight opening (NB + r0º) only nominally reduces the illuminance levels, particularly at the innermost regions of the floor area.

Applying untilted blinds in both window openings (w0º+ w0º or w0º + r0º) significantly reduce the illuminance levels near the windows, but the reductions at the innermost parts of the floor (near the back wall) are again relatively small. A positive aspect with this configuration is that the illuminance levels are much more uniform along the depth of the room.

The lowest illuminance values are obtained when the blinds in the view opening are tilted. A blind tilt of 45º provides low illuminance values that are quite uniform throughout the floor space.

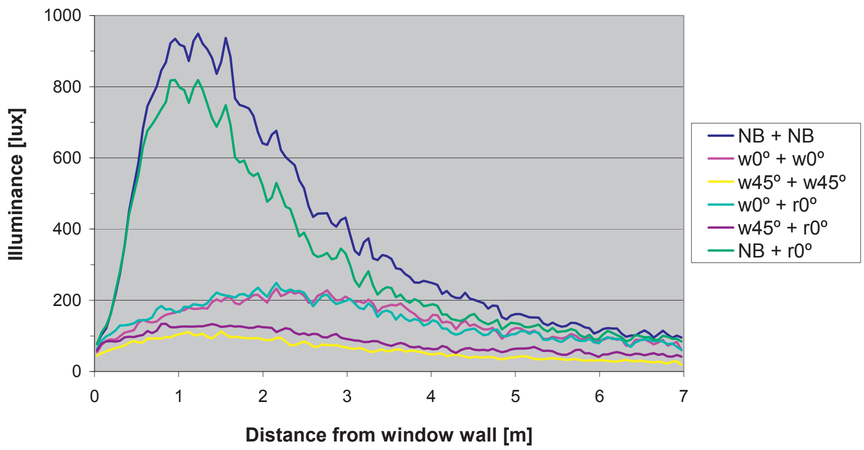


Figure 7-1 Average illuminance on the floor for different blind configurations in the view opening and daylight opening as a function of the distance from the window wall under overcast sky conditions (S1).

From these simulations it is clear that the properties and configuration of the blinds play a major role in determining the illuminance levels in a room under overcast sky conditions. All configurations that include blinds seem to reduce the illuminance levels of the floor compared to the situation without blinds. However, blinds can be used to provide a more uniform light distribution, and blind tilting can be used to reduce and regulate the illuminance levels if so desired.

7.5.2 Ceiling illuminance

Results from simulations of ceiling illuminance levels for different blind configurations are illustrated in Figure 7-2. In this case, the configuration without blinds in both the view opening and the daylight opening (NB + NB) does not provide the highest illuminance values.

Here, the configuration with no blinds in the view opening and untilted reflective blinds in the daylight opening (NB + r0º) provides higher illuminance values near the window, and comparable values at the deeper end of the ceiling.

The configuration with untilted white blinds in the view opening and untilted reflective blinds in the daylight opening (w0º + r0º) provides a relatively uniform illuminance distribution over the ceiling, and with relatively high values in the inner half of the room. With respect to ceiling luminance, the configuration with a reflective blind provides higher values than the white blind (w0º + w0º) in the inner half of the room.

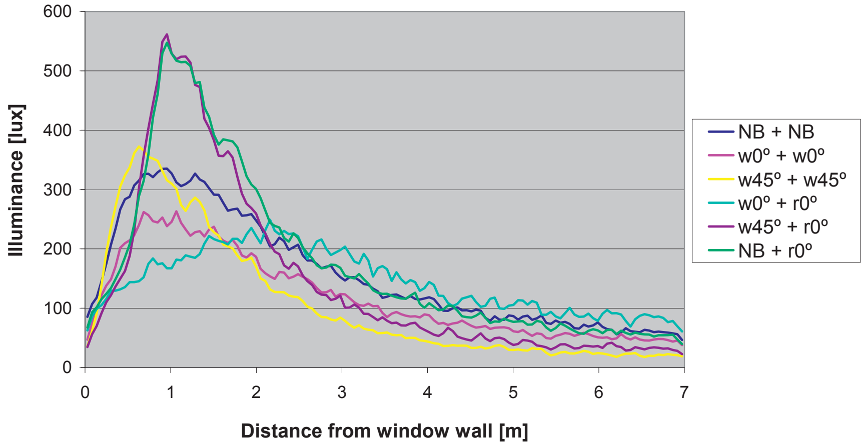


Figure 7-2 Average illuminance on the ceiling for different blind configurations as a function of the distance from the window wall under overcast sky conditions (S1).

Again, it is clear that the properties and configuration of the blinds play a major role in determining the illuminance levels under overcast sky conditions. With respect to ceiling illuminance levels, blinds can be used to increase or to lower the levels, as well as to provide a more uniform distribution across the ceiling.

7.6 Results for high sun conditions

In direct sunlight it is important that the blinds provide sunlight cut-off. For reflective blinds it is also important that the reflected light is directed upwards (above the horizontal plane, so as to avoid glare from specular reflections directed downwards).

As discussed in 4.6, for high projected solar elevations, the reflective blinds should be tilted slightly above the cut-off position to avoid downward directed specular reflections. For white blinds it could be desired to keep the blinds untilted so as to enhance the view in the horizontal direction. These considerations are relevant for the choice of blind configurations to be investigated.

7.6.1 Scene 8

Scene 8 is characterised by a solar elevation angle of 50º and an azimuth difference angle of 15º. For this daylight condition the resulting projected solar elevation is 50.97º. This means that for the reflective blind (*S/W* = 0.6) the blind tilt at sunlight cut-off is -28.78º as given in Table 4-3. Under these conditions, Figure 4-8 shows that the reflected sunlight will be directed downwards when the blind is tilted at the sunlight cut-off angle.

In order to assure that the specularly reflected light is directed upwards a slightly higher tilt angle (β) of -20º is considered. Equation 4.4 can here be used to calculate that the angle (projected into the yz-plane) above the horizontal of the reflected sunlight (γ'_{int}) will be approximately 11º. This configuration is expected to redirect sunlight relatively far into the interiors and, hopefully, to provide a relatively even light distribution at the floor level.

For the white blind (*S/W* = 0.9) the blind tilt at sunlight cut-off is -16.45º as given in Table 4-3. It is here considered most appropriate to keep the white blind untilted so as to enhance the view in the horizontal direction, as discussed above. In addition, a blind tilt of 45º is considered. As for overcast conditions, this could also here be relevant when reductions in daylight levels are required, when additional glare protection is needed, or also when the occupants have neglected to adjust the blinds after prior sunlight conditions requiring larger blind tilts. Finally, configurations without blinds and with blinds fully closed are also considered.

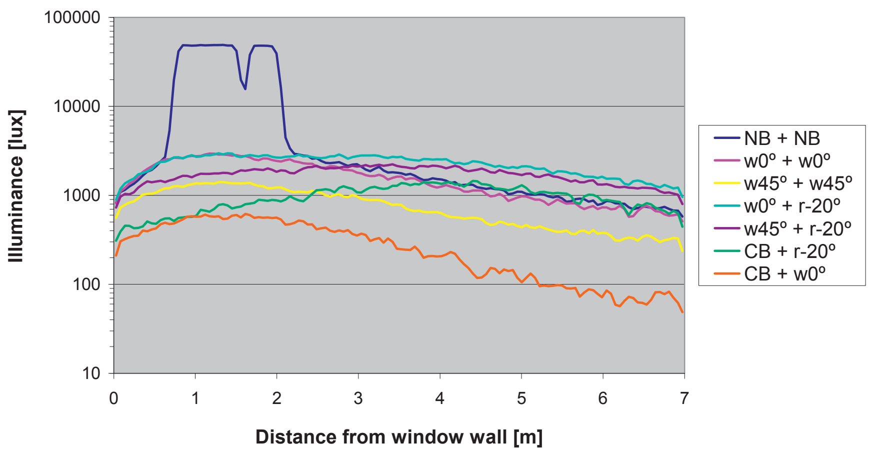


Figure 7-3 Average illuminance on the floor for different blind configurations as a function of the distance from the window wall under high sun conditions (S8). The dip seen in the results without blinds (NB) is caused by the separation of the two window openings.

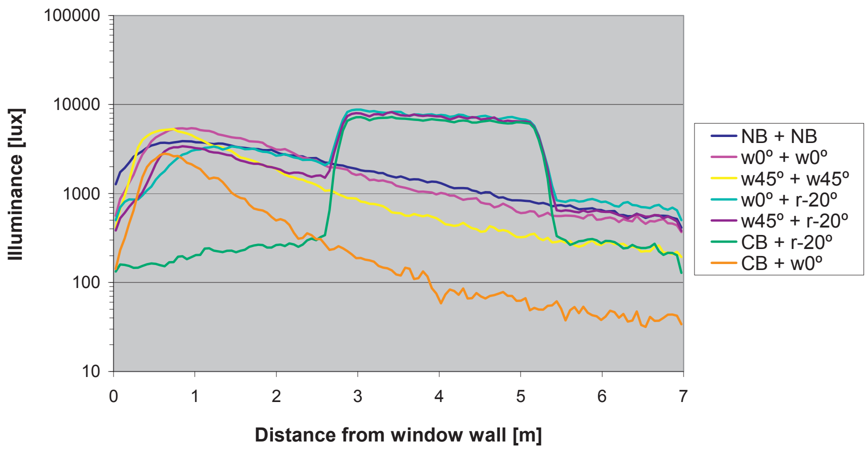


Figure 7-4 Average illuminance on the ceiling for different blind configurations as a function of the distance from the window wall under high sun conditions (S8).

7.6.2 Scene 9

Scene S9 is characterised by a solar elevation angle of 50º and an azimuth difference angle of 45º. For this daylight condition the resulting projected solar elevation is 59.32º. This means that for the reflective blind ($S/W = 0.6$) the blind tilt at sunlight cut-off is -41.49º as given in Table 4-3. As for S8, also here the reflected sunlight will be directed downwards when the blind is tilted at the sunlight cut-off angle.

In order to assure that the specularly reflected light is directed upwards a slightly higher tilt angle (β) of -25º is considered. Again, equation 4.4 can here be used to calculate that the angle (projected into the yz-plane) above the horizontal of the reflected sunlight (γ'_{int}) will be approximately 9º.

For the white blind ($S/W = 0.9$) the blind tilt at sunlight cut-off is -31.98º as given in Table 4-3. Again it is considered most appropriate to keep the white blind untilted so as to enhance the view in the horizontal direction. In addition, a blind tilt of 45º is considered for the same reason as given above.

Finally, configurations without blinds and with blinds fully closed are also considered.

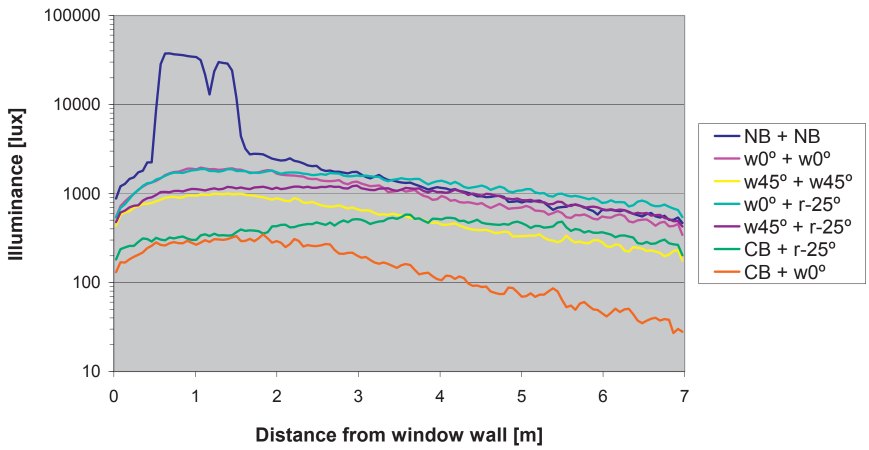


Figure 7-5 Average illuminance on the floor for different blind configurations as a function of the distance from the window wall under high sun conditions (S9).

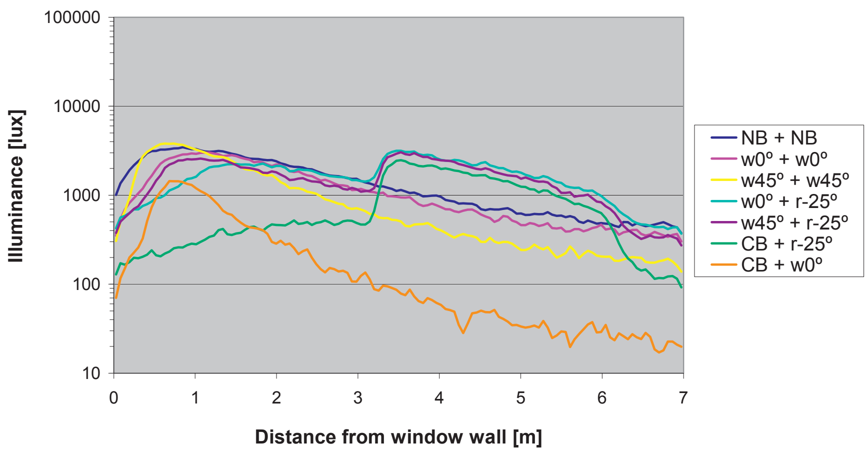


Figure 7-6 Average illuminance on the ceiling for different blind configurations as a function of the distance from the window wall under high sun conditions (S9).

7.6.3 Scene 10

Scene 10 is characterised by a solar elevation angle of 50º and an azimuth difference angle of 75º. For this daylight condition the resulting projected solar elevation is 77.75º. This means that for the reflective blind (*S/W* = 0.6) the blind tilt at sunlight cut-off is -70.43º as given in Table 4-3. As for the other high sun conditions considered (S8 and S9), also here the reflected sunlight will be directed downwards when the blind is tilted at the sunlight cut-off angle.

It is again chosen to consider a higher tilt angle (β) of -35º to assure that the specularly reflected light is directed upwards. Equation 4.4 can again be used to calculate that the angle (projected into the yz-plane) above the horizontal of the reflected sunlight (γ'_{int}) will be approximately 8º.

For the white blind (*S/W* = 0.9) the blind tilt at sunlight cut-off is -66.74º as given in Table 4-3. Again it considered of interest to keep the white blind untilted so as to enhance the view in the horizontal direction. In addition, a blind tilt of 45º is considered for the same reason as given above.

Finally, configurations without blinds and with blinds fully closed are also considered.

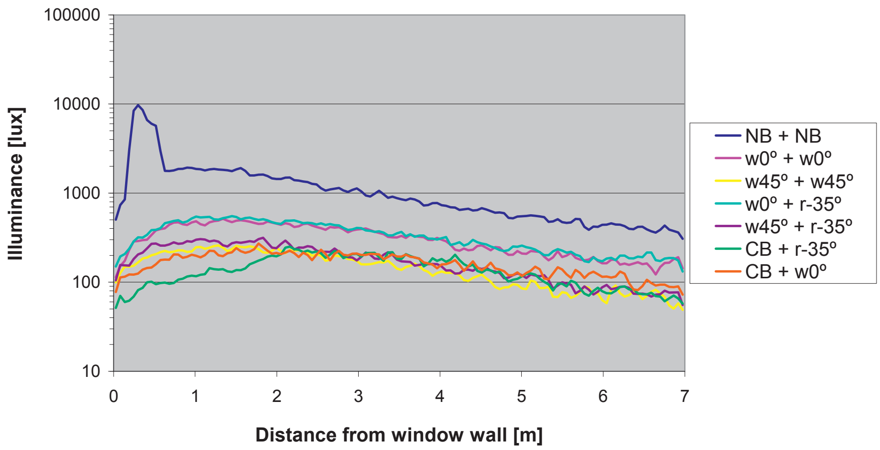


Figure 7-7 Average illuminance on the floor for different blind configurations as a function of the distance from the window wall under high sun conditions (S10).

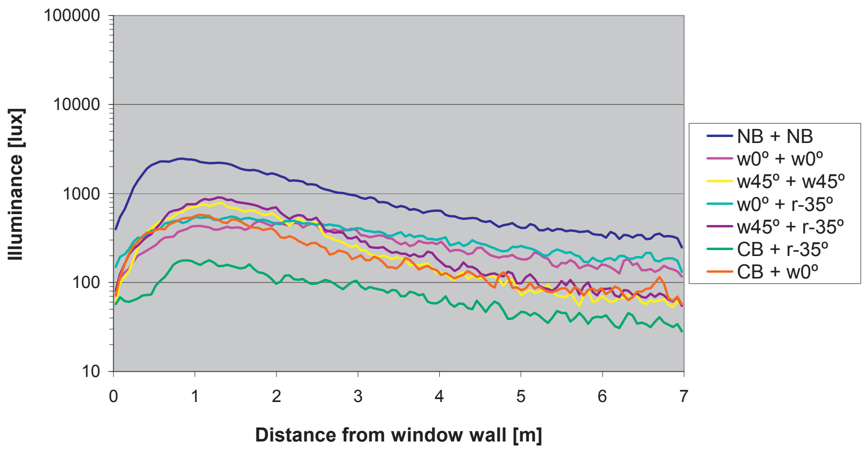


Figure 7-8 Average illuminance on the ceiling for different blind configurations as a function of the distance from the window wall under high sun conditions (S10).

7.6.4 Conclusions - high sun

The results show that the illuminance levels on the floor and ceiling depend on the blind type and the blind tilt. In addition, the azimuth difference angle is of great importance.

For scene 8 ($\Delta\alpha_s$ = 15º) the reflective blind have the ability to redirect sunlight towards the inner parts of the ceiling. This provides a relatively even illuminance distribution at the floor with high illuminance levels that could be more than sufficient to displace all electric lighting. The configuration with the reflective blind in the daylight opening provides higher floor illuminance levels than the configuration with a white blind for this scene.

For scene 9 ($\Delta\alpha_s$ = 45º) most of the sunlight reflected off the reflective blind is redirected towards the walls, thus providing lower average illuminance levels at the ceiling. Since the walls are less reflective (50%) than the ceiling (70%) the illuminance levels at the floor drops compared to scene 8. However, the use of the reflective blind tilted for daylight redirection still provides a relatively even light distribution at the floor for the full depth of the reference space. Again, the reflective blind performs slightly better than the white blind with respect to floor illuminance levels.

For scene 10 ($\Delta\alpha_s$ = 75º) the sunlight reaching the reflective blind is redirected towards the walls. Compared to scenes 8 and 9, scene 10 gives lower illuminance levels at both the ceiling and floor. For this scene the illuminance levels on the floor drops significantly towards the back of the room. This can be explained by the fact that the sunlight is reflected towards the wall region near the window facade. In addition, due to the high projected solar elevation, a large portion of the light specularly reflected from a slat hits the overlying slat. This limits the effect of the reflective blind. For scene 10 it would therefore have been preferable to apply blinds with a larger spacing to width ratio.

7.7 Results for intermediate sun conditions

7.7.1 Scene 5

Scene 5 is characterised by a solar elevation angle of 30º and an azimuth difference angle of 15º. For this daylight condition the resulting projected solar elevation is 30.87º. This means that for the reflective blind ($S/W = 0.6$) the blind tilt at sunlight cut-off is 0.13º as given in Table 4-3. Under these conditions, Figure 4-8 shows that the reflected sunlight will be directed upwards when the blind is tilted at the sunlight cut-off angle.

It is therefore here chosen to consider a tilt angle corresponding to the sunlight cut-off angle plus 1º to allow for mechanical tolerances. This gives a tilt angle (β) of -1.13º. Equation 4.4 can here be used to calculate that the angle (projected into the yz-plane) above the horizontal of the reflected sunlight (γ'_{int}) will be approximately 33º.

This configuration is therefore not expected to redirect sunlight far into the interiors. However, it is considered most important to stop direct sunlight from passing between the blind slats, so tilt angles lower than the sunlight cut-off angle are not considered.

For the white blind ($S/W = 0.9$) the blind tilt at sunlight cut-off is 19.71º as given in Table 4-3. Again, a blind tilt that is 1º higher than this is considered to allow for mechanical tolerances. In addition, a blind tilt of 45º is considered. As discussed earlier, this could also here be relevant when reductions in daylight levels are required, when additional glare protection is needed, or also when the occupants have neglected to adjust the blinds after prior sunlight conditions requiring larger blind tilts.

Finally, configurations without blinds and with blinds fully closed are also considered.

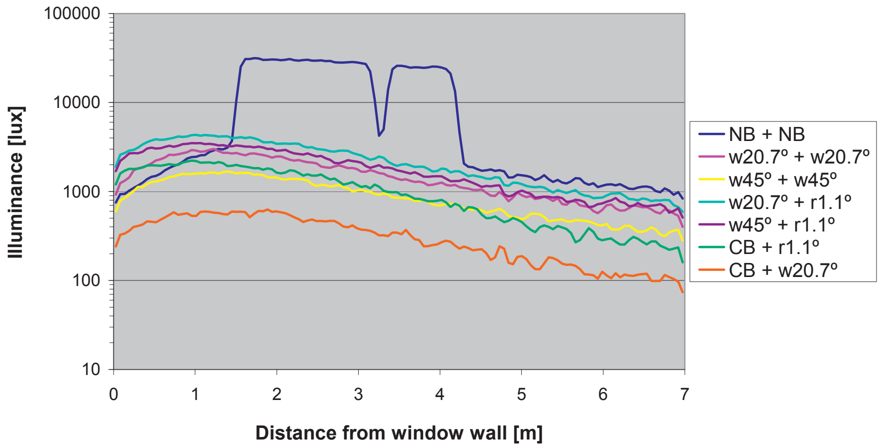


Figure 7-9 Average illuminance on the floor for different blind configurations as a function of the distance from the window wall under intermediate sun conditions (S5).

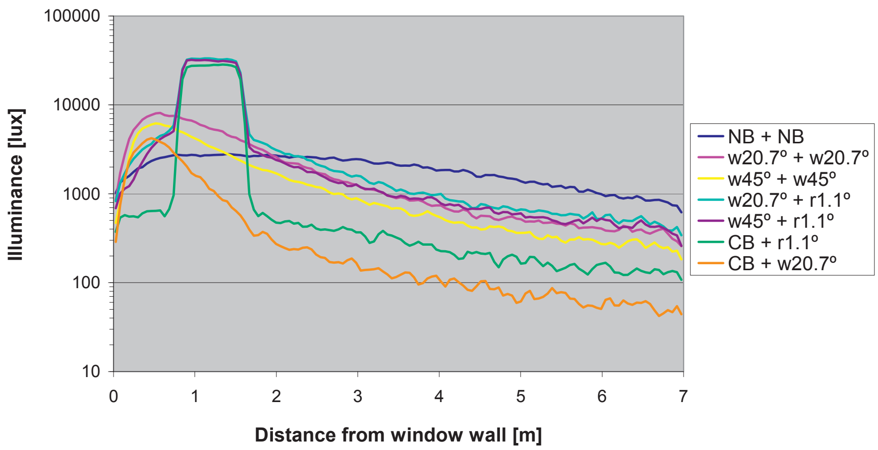


Figure 7-10 Average illuminance on the ceiling for different blind configurations as a function of the distance from the window wall under intermediate sun conditions (S5).

7.7.2 Scene 6

Scene 6 is characterised by a solar elevation angle of 30º and an azimuth difference angle of 45º. For this daylight condition the resulting projected solar elevation is 39.23º. This means that for the reflective blind (*S/W* = 0.6) the blind tilt at sunlight cut-off is -11.54º as given in Table 4-3. Under these conditions, Figure 4-8 shows that the reflected sunlight will be directed upwards when the blind is tilted at the sunlight cut-off angle.

As for S5, it is therefore also here chosen to consider a tilt angle corresponding to the sunlight cut-off angle plus 1º to allow for mechanical tolerances. This gives a tilt angle (β) of -10.54º. Equation 4.4 can here be used to calculate that the angle (projected into the yz-plane) above the horizontal of the reflected sunlight (γ'_{int}) will be approximately 18º.

This configuration is again not expected to redirect sunlight as far into the interiors as could be desired. However, it is also here considered most important to stop direct sunlight from passing between the blind slats, so tilt angles lower than the sunlight cut-off angle are not considered.

For the white blind (*S/W* = 0.9) the blind tilt at sunlight cut-off is 4.97º as given in Table 4-3. Again, a blind tilt that is 1º higher than this is considered to allow for mechanical tolerances. In addition, a blind tilt of 45º is considered. As discussed earlier, this could be relevant when reductions in daylight levels are required, when additional glare protection is needed, or also when the occupants have neglected to adjust the blinds after prior sunlight conditions requiring larger blind tilts.

Finally, configurations without blinds and with blinds fully closed are also considered.

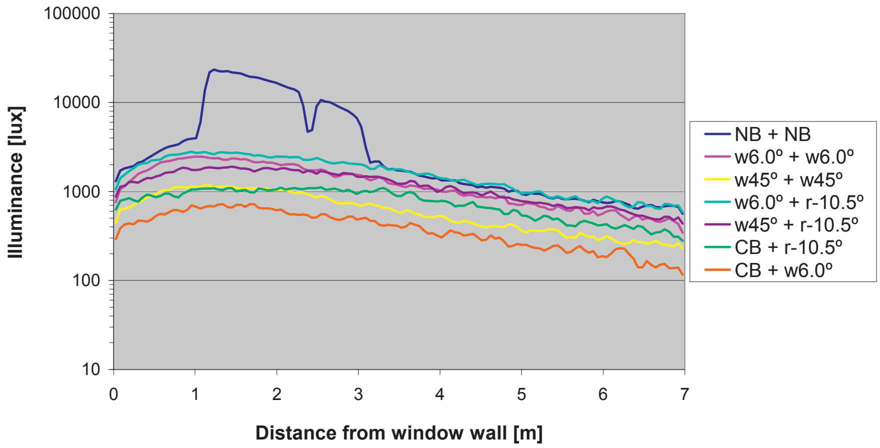


Figure 7-11 Average illuminance on the floor for different blind configurations as a function of the distance from the window wall under intermediate sun conditions (S6).

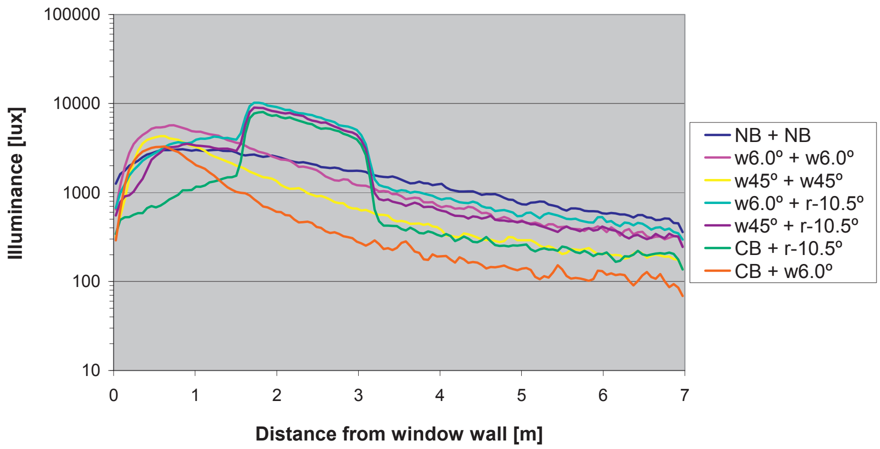


Figure 7-12 Average illuminance on the ceiling for different blind configurations as a function of the distance from the window wall under intermediate sun conditions (S6).

7.7.3 Scene 7

Scene 7 is characterised by a solar elevation angle of 30º and an azimuth difference angle of 75º. For this daylight condition the resulting projected solar elevation is 65.85º. This means that for the reflective blind (*S/W* = 0.6) the blind tilt at sunlight cut-off is -51.65º as given in Table 4-3. Under these conditions, as seen for high sun conditions, also here the reflected sunlight will be directed downwards when the blind is tilted at the sunlight cut-off angle.

It is therefore here again chosen to consider a higher tilt angle (β) of -30º to assure that the specularly reflected light is directed upwards. Again, equation 4.4 can here be used to calculate that the angle (projected into the yz-plane) above the horizontal of the reflected sunlight (γ'_{int}) will be approximately 6º.

For the white blind (*S/W* = 0.9) the blind tilt at sunlight cut-off is -44.25º as given in Table 4-3. Again it considered most appropriate to keep the white blind untilted so as to enhance the view in the horizontal direction. In addition, a blind tilt of 45º is considered for the same reasons as given earlier.

Finally, configurations without blinds and with blinds fully closed are also considered.

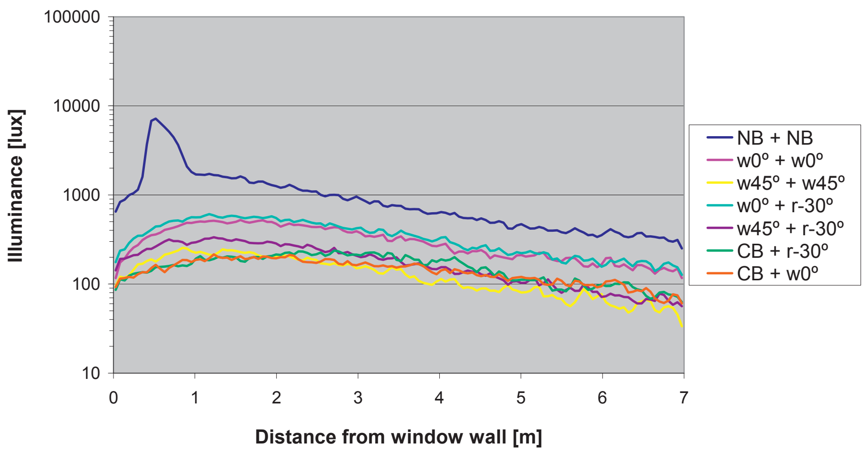


Figure 7-13 Average illuminance on the floor for different blind configurations as a function of the distance from the window wall under intermediate sun conditions (S7).

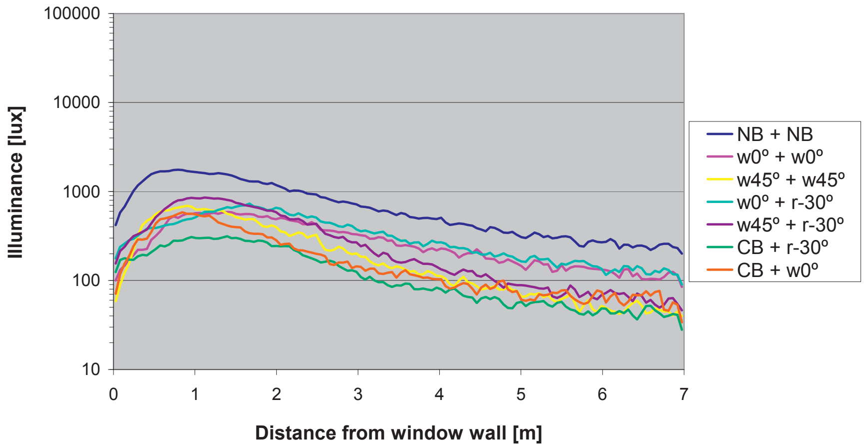


Figure 7-14 Average illuminance on the ceiling for different blind configurations as a function of the distance from the window wall under intermediate sun conditions (S7).

7.7.4 Conclusions - intermediate sun

The results again show that the illuminance levels on the floor and ceiling depend on the blind type and the blind tilt. In addition, the azimuth difference angle is also here of great importance.

For scene 5 ($\Delta\alpha_s = 15°$) the configurations with a reflective blind have the ability to redirect sunlight towards the ceiling, but only towards part located near the window facade. For this reason the floor illuminance drops considerably towards the back wall.

For scene 6 ($\Delta\alpha_s = 45°$) the sunlight is reflected at a lower angle (γ'_{int} ~18°) and the resulting floor illuminance levels are somewhat more uniform across the depth of the room.

For scene 7 ($\Delta\alpha_s = 75°$) the light from the reflective blind is reflected towards the side wall, and because of the large azimuth difference angle the light hits the wall relatively near the window facade. As noted before, the reflectance of the side wall is lower than that of the ceiling, and this also contributes negatively to the resulting illuminance levels. The results show that the reflective blind and the white blind (located in the daylight opening) both provide similar floor illuminance levels across the depth of the room for this daylight scene.

7.8 Results for low sun conditions

7.8.1 Scene 2

Scene 2 is characterised by a solar elevation angle of 10º and an azimuth difference angle of 15º. For this daylight condition the resulting projected solar elevation is 10.35º. This means that for the reflective blind (*S/W* = 0.6) the blind tilt at sunlight cut-off is 25.83º as given in Table 4-3. Under these conditions, Figure 4-8 shows that the reflected sunlight will be directed upwards when the blind is tilted at the sunlight cut-off angle.

It is therefore here chosen to consider a tilt angle corresponding to the sunlight cut-off angle plus 1º to allow for mechanical tolerances. This gives a tilt angle (β) of -26.83º. Equation 4.4 can here be used to calculate that the angle (projected into the yz-plane) above the horizontal of the reflected sunlight (γ'_{int}) will be approximately 64º.

This configuration is therefore not expected to redirect much sunlight into the interiors, since most of the light reflected off from the slats will be directed towards the lower side of the overlying slat. However, it is also here considered most important to stop direct sunlight from passing between the blind slats, so tilt angles lower than the sunlight cut-off angle are not considered.

For the white blind (*S/W* = 0.9) the blind tilt at sunlight cut-off is 51.95º as given in Table 4-3. Again, a blind tilt that is 1º higher than this is considered to allow for mechanical tolerances.

For this scene, a blind tilt of 45º is not considered, since this tilt is lower than the cut-off tilt. However, configurations without blinds and with blinds fully closed are again considered, as before.

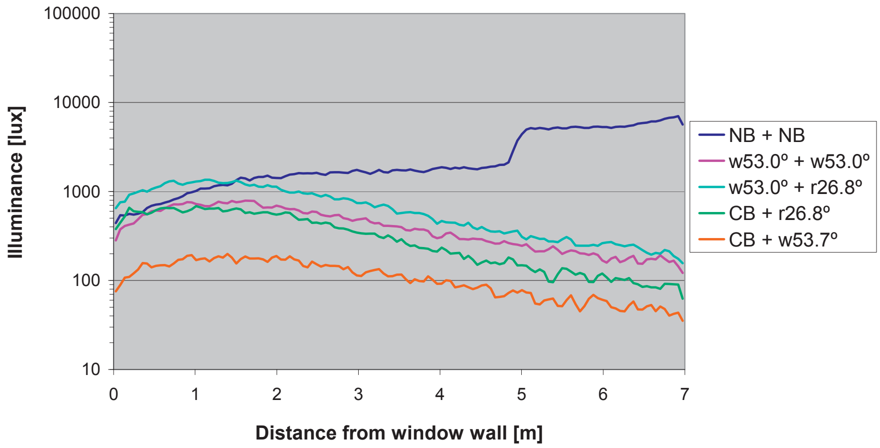


Figure 7-15 Average illuminance on the floor for different blind configurations as a function of the distance from the window wall under low sun conditions (S2).

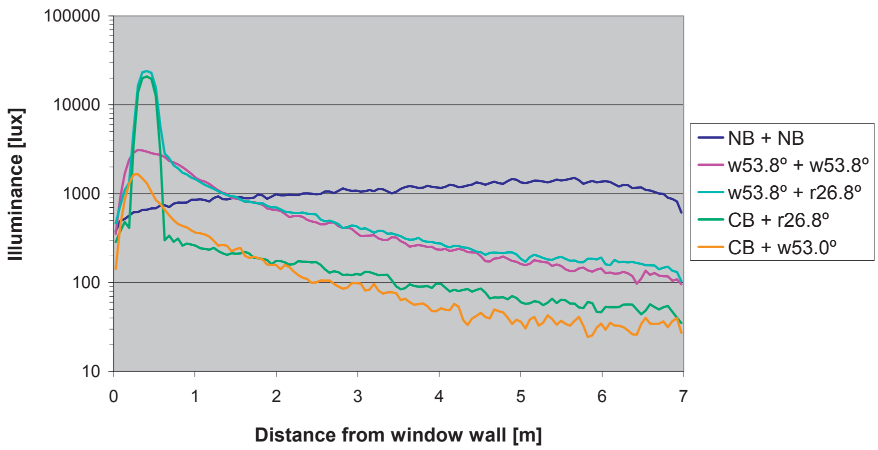


Figure 7-16 Average illuminance on the ceiling for different blind configurations as a function of the distance from the window wall under low sun conditions (S2).

7.8.2 Scene 3

Scene 3 is characterised by a solar elevation angle of 10º and an azimuth difference angle of 45º. For this daylight condition the resulting projected solar elevation is 14.00º. This means that for the reflective blind (*S/W* = 0.6) the blind tilt at sunlight cut-off is 21.60º as given in Table 4-3. Under these conditions, Figure 4-8 shows that the reflected sunlight will be directed upwards when the blind is tilted at the sunlight cut-off angle.

It is therefore here chosen to consider a tilt angle corresponding to the sunlight cut-off angle plus 1º to allow for mechanical tolerances. This gives a tilt angle (β) of -22.60º. Equation 4.4 can here be used to calculate that the angle (projected into the yz-plane) above the horizontal of the reflected sunlight (γ'_{int}) will be approximately 59º.

This configuration is not expected to redirect sunlight deep into the interiors, since most of the reflected light from one slat will be directed towards the lower side of the overlying slat, and also, for the transmitted light the projected angle (γ'_{int} = 59º) is simply too large. However, as before, tilt angles lower than the sunlight cut-off angle are not considered.

For the white blind (*S/W* = 0.9) the blind tilt at sunlight cut-off is 46.84º as given in Table 4-3. Again, a blind tilt that is 1º higher than this is considered to allow for mechanical tolerances.

For this scene, a blind tilt of 45º is not considered, since this tilt is lower than the cut-off tilt. However, configurations without blinds and with blinds fully closed are again considered, as before.

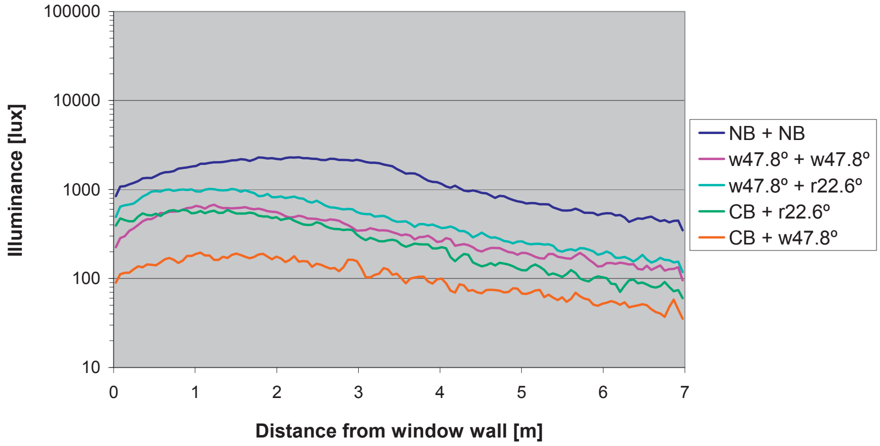


Figure 7-17 Average illuminance on the floor for different blind configurations as a function of the distance from the window wall under low sun conditions (S3).

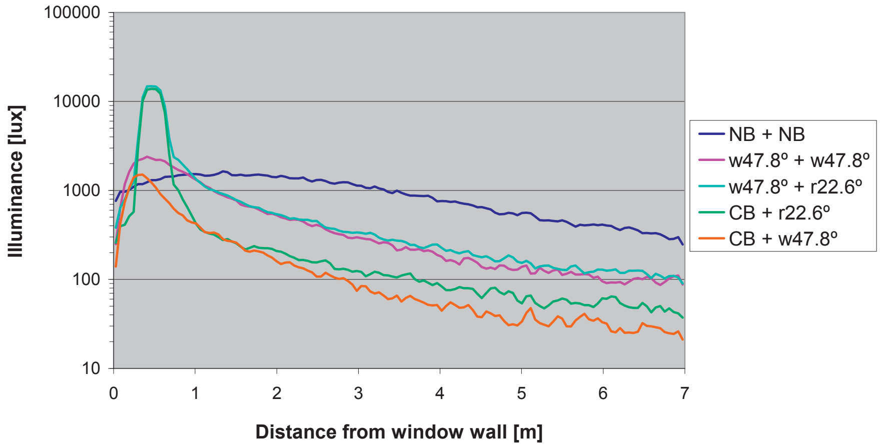


Figure 7-18 Average illuminance on the ceiling for different blind configurations as a function of the distance from the window wall under low sun conditions (S3).

7.8.3 Scene 4

Scene 4 is characterised by a solar elevation angle of 10º and an azimuth difference angle of 75º. For this daylight condition the resulting projected solar elevation is 34.27º. This means that for the reflective blind (*S/W* = 0.6) the blind tilt at sunlight cut-off is -4.54º as given in Table 4-3. Under these conditions, Figure 4-8 shows that the reflected sunlight will be directed upwards when the blind is tilted at the sunlight cut-off angle.

It is therefore here chosen to consider a tilt angle corresponding to the sunlight cut-off angle plus 1º to allow for mechanical tolerances. This gives a tilt angle (β) of -3.54º for the reflective blind. Equation 4.4 can here be used to calculate that the angle (projected into the yz-plane) above the horizontal of the reflected sunlight (γ'_{int}) will be approximately 27º.

This configuration is expected to redirect sunlight into the interiors, but only towards the side walls, and not as deep as could be desired with respect to obtaining high luminance levels in the back of the room. However, as before, tilt angles lower than the sunlight cut-off angle are not considered.

For the white blind (*S/W* = 0.9) the blind tilt at sunlight cut-off is 13.79º as given in Table 4-3. Again, a blind tilt that is 1º higher than this is considered to allow for mechanical tolerances. In addition, a blind tilt of 45º is considered for the same reasons as given earlier.

Finally, configurations without blinds and with blinds fully closed are also considered.

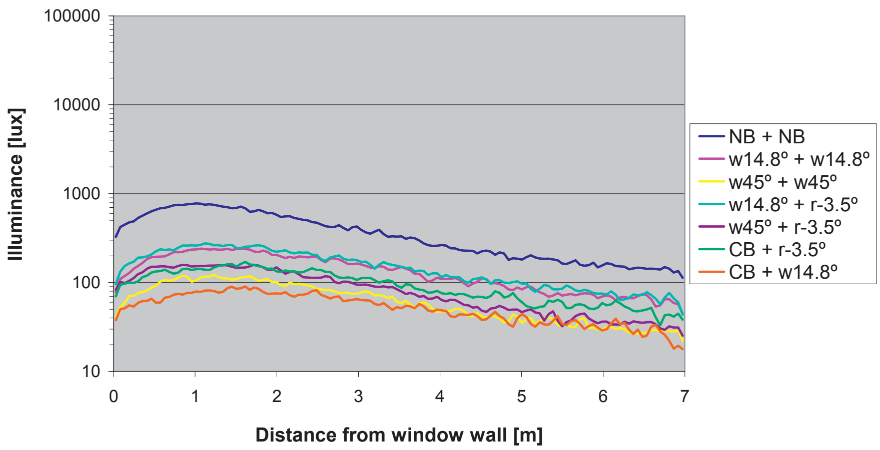


Figure 7-19 Average illuminance on the floor for different blind configurations as a function of the distance from the window wall under low sun conditions (S4).

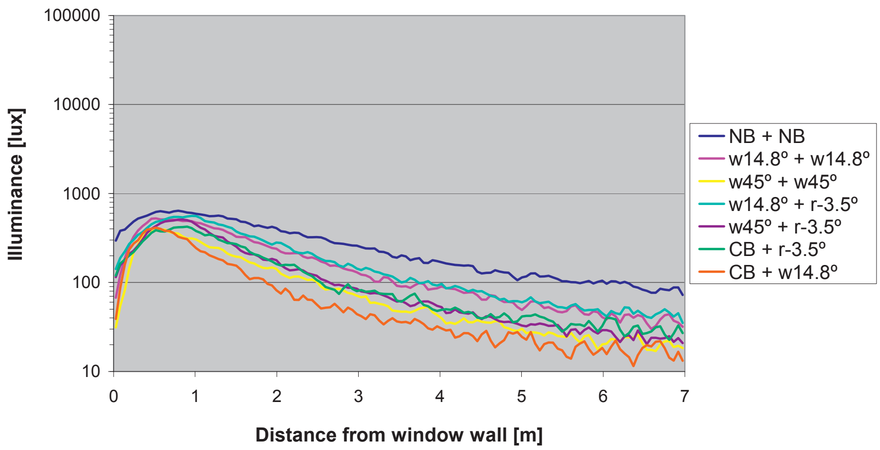


Figure 7-20 Average illuminance on the ceiling for different blind configurations as a function of the distance from the window wall under low sun conditions (S4).

7.8.4 Conclusions – low sun

The illuminance levels on the floor and ceiling again depend strongly on the blind type and blind tilt.

For scene 2 ($\Delta\alpha_s$ = 15°), the sunlight reflected off from the reflective slat has a steep angle (γ'_{int} = 64°), and the light that escapes the overlying slat will be directed towards the ceiling very close to the window wall. For this reason the illuminance on the floor also drops significantly with increasing distance from the window wall, and the effect of the reflective blind (compared to the white blind) is rather limited.

For scene 3 ($\Delta\alpha_s$ = 45°), with no blinds (NB + NB), the direct sunlight hits the side wall. This is why there are no peaks on the floor illuminance chart for this configuration. For the reflective blind, most of the reflected light is redirected towards the overlying slat, some is redirected towards the wall (near the window), and only a small part is redirected towards the ceiling (also near the window). Therefore, as for scene 2, the illuminance on the floor drops significantly with increasing distance from the window wall.

For scene 4 ($\Delta\alpha_s$ = 75°) the configurations with reflective blinds and white blinds perform very similarly with respect to illuminance levels on floor and ceiling. For this scene it is also noteworthy that the illuminance levels near the back wall are quite low (about 100 lux for both floor and ceiling) even for the configuration without any blinds present (NB + NB). There are several reasons for these low levels:

i) The radiation from a low sun is less intense than that from a high sun, since the light travels a longer distance through the atmosphere. This effect is quantified by equation 5.8.
ii) The large azimuth difference angle ($\Delta\alpha_s$ = 75º) reduces the illuminance from direct sunlight on the window surface according to equations 5.11 and 5.9.
iii) The large angle of incidence also reduces the transmission through the glass panes.
iv) As a result of the large azimuth difference angle, direct sunlight hits the side wall relatively near the window facade. This provides relatively high illuminance values on the floor and ceiling near the window facade, but much lower values near the back wall.

7.9 Summary and conclusions

In this chapter the illuminance levels on floor and ceiling of a sidelighted space were studied. The space was provided with both a (lower) view window as well as an elevated daylight opening, and the effect of different blind types and blind tilts has been considered

The results show that a reflective blind positioned in the elevated daylight opening generally provides higher illuminances than a white blind in the same window opening. However, the results depend to a large degree on the outside daylight conditions, and the reflective blind does not always provide (significantly) higher illuminance levels.

In some respect it can be concluded that it is not straight forward to understand which solution is the best for different daylight conditions and particularly *why* the illuminance levels wary the way that the results indicate. The optical function of the space itself, including the two window openings as well as the contribution of internally reflected light seem to add to the optical complexity of the venetian blind solutions themselves.

This emphasises the need for simpler analytical tools that can be used to describe the system itself, and not the effect of the “system plus room” combination. In the next chapter one particular attribute of the venetian blind systems that is important for the interior lighting quality is discussed; the light transmittance through the blind system. This is only a first example to be considered of an attribute of a blind system that is completely independent from the characteristics of the interior space in which the blind is used.

8 Light transmittance through venetian blind systems

Where there is much light, the shadow is deep.

Johann Wolfgang Von Goethe

8.1 Introduction

In the previous chapter the illuminance distributions in a space supplied with various solutions of daylight redirecting blinds and traditional white blinds were studied. The results provide insights into system performance, but it is not straightforward to extract the actual optical performance of the system since the space itself has a large influence on the obtained results.

In this chapter the light transmittance of the venetian blind systems is studied. This is one example of a parameter that does not depend on the space in which the system is applied.

The light transmittance of a venetian blind system is clearly an important parameter that influences the illuminance levels within the interiors. In fact, under a given daylight scene, and provided that the distribution of the light after passing the blinds is the same, the illuminance levels obtained in the interiors are directly proportional to the transmittance of the system.

The efficiency of venetian blinds with respect to light transmittance has been the subject of several studies. The earliest investigations were carried out by Parmelee and Aubele (1952) and led to two optical blind models for slats with specular and diffuse surfaces respectively. Models for light transmittance through blinds with specular and diffuse slat surfaces were also developed by Pfrommer et al. (1996). Here, the two models were combined into a single model that also can describe slat surfaces that are neither completely specular nor completely diffuse. Similar models have also been developed for the use in energy calculation software such as the WIS model and EnergyPlus model. A discussion and comparative analysis of the different models is provided by Chantrasrisalai and Fisher (2004).

However, these models can only be applied to slat-type shading systems, and are all based on some simplifying assumptions. Of the models mentioned above, only the Pfrommer model includes corrections for slat curvature. On the other hand the Pfrommer model considers only the first two diffuse reflections on the slats and according to Chantrasrisalai and Fisher tends to underpredict measured transmittance when a large amount of sunlight is transmitted by reflections. Another simplification applied to these models is the assumption that the diffuse irradiance distribution is isotropic.

A 3D ray tracing approach as that provided by TracePro simulations can be used more generally for all types of surfaces and taking into account the slat curvature and the diffuse sky distributions as well. In addition, a 3D ray tracing approach can be used for various types of fenestration systems, and not only for slat-type devices.

The light transmittance through the fenestration systems is given by:

$$\tau = \frac{\phi_{\mathrm{int}}}{\phi_{ext}} \tag{8.1}$$

The transmittance describes the ratio of the total luminous flux on the interior side of the fenestration system (Φ_{int}) to the total luminous flux on the exterior side of the system (Φ_{ext}).

8.2 Double glazing unit

As given in section 7.2, the window panes in the doubled glazing unit are modelled as non-absorbing with a refractive index (n) of 1.52. For this type of glazing the simulations show that the transmittance through the double glazing varies significantly with the angular distribution of the incident light.

In Table 8-1, the transmittance is given for the 10 daylight scenes that have been investigated. As can be expected, the transmittance is lowest for the daylight scenes with the most oblique light incidence; that is scene 4, 7 and 10, where the sunlight enters with an azimuth difference angle of 75 º. The transmittance is highest when the light is incident in a direction that is close to the window normal as is the case for scene 2. In this case, slightly above 4% of the (unpolarised) light is reflected at each of the four glass-air interfaces, and the resulting value of 84% transmittance therefore seems quite reasonable.

Table 8-1 Transmittance through a double glazing for different daylight scenes.

Scene	Solar elevation	Azimuth difference	Transmittance [%]
1	30º	not relevant	74
2	10º	15º	84
3	10º	45º	81
4	10º	75º	53
5	30º	15º	83
6	30º	45º	78
7	30º	75º	54
8	50º	15º	79
9	50º	45º	70
10	50º	75º	54

8.3 Diffuse blind slats

The ability to supply daylight to the interiors is one of the main reasons for having window openings in buildings. Fenestration systems for shading and glare control as a rule reduce the supply of daylight. For venetian blinds, the blind geometry (including blind tilt) as well as the reflectance properties of the blind slats will affect the amount of daylight that enters through the fenestration system. In this section the effect on daylight supply for various spacing to width ratios and reflectance properties is considered.

The simulations are carried out for flat blinds with zero thickness and a perfectly diffusely reflecting (lambertian) surface. The blinds are positioned on the interior side of a double glazing. The transmittance results are corrected for the transmittance of the double glazing unit (as given in Table 8-1). This means that for perfectly transmitting blinds (or no blinds) the transmittance will be equal to 1. It also means that the actual transmittance values for the system of double glazing unit and interior blinds will be lower than the values presented below.

8.3.1 Overcast sky

In overcast sky conditions, the daylight transmittance through the fenestration system is largest when the blinds are completely raised. Yet, studies of user patterns show that people tend to leave the blinds lowered, even in overcast skies (see section 2.5.). It is therefore relevant to investigate the daylight transmittance through lowered venetian blinds even for overcast sky conditions.

As shown earlier, untilted blinds will give the best possibility for view in the horizontal viewing direction. Following from this, it is here considered the daylight transmittance through untilted venetian blinds in overcast sky conditions (scene 1).

In Figure 8-1, the transmittance through interior blinds is shown. It is seen that the transmittance is highest for the blind configuration with the least overlap (*S/W* = 0.9). As can be expected, the transmittance increases with increasing slat reflectance for all spacing to width ratios.

The results show that the slat reflectance of diffuse blinds can be very important for the daylight transmittance through the blinds. As an illustration, a blind with *S/W* of 0.8 could be considered. If the slat reflectance is 0.5 the transmittance through the blind is about 0.43. Increasing the slat reflectance to 0.9 results in a transmittance of about 0.62, thus the daylight supply is increased with nearly 50%.

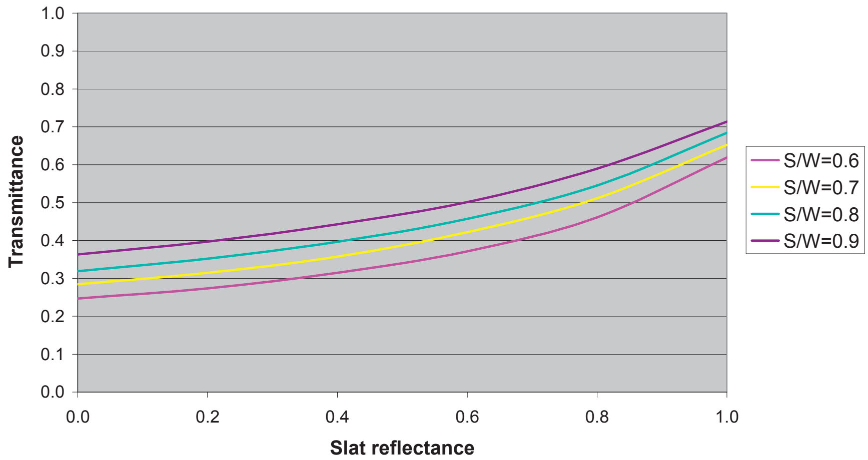


Figure 8-1 Transmittance through untilted blinds with flat diffusely reflecting slats of zero thickness under overcast sky conditions (S1).

It is of interest to compare these results with results obtained by so-called one-dimensional models, as discussed by Chantrasrisalai and Fisher (2004). In Figure 8-2 is shown the transmittance through untilted blinds obtained by different one-dimensional models according to Chantrasrisalai and Fisher. The results are similar to those obtained by the TracePro simulations. However, the *S/W* ratio is not specified in the work by Chantrasrisalai and Fisher, so a direct comparison is not possible. Furthermore, there are two assumptions that are different:

- The one-dimensional methods discussed by Chantrasrisalai and Fisher assume an isotropic sky, while the TracePro simulations are based on an overcast sky with varying illuminance according to equation 5.3 (CIE Traditional overcast sky).

- Secondly, the TracePro simulations include the back reflections from the double glazing. This means that some of the light reflected back from the slats towards the exterior will still be transmitted due to back reflections from the glazing. This will increase the transmittance obtained from the TracePro simulations compared to the one-dimensional methods. The effect of this back reflectance is assumed to be largest for high slat reflectances.

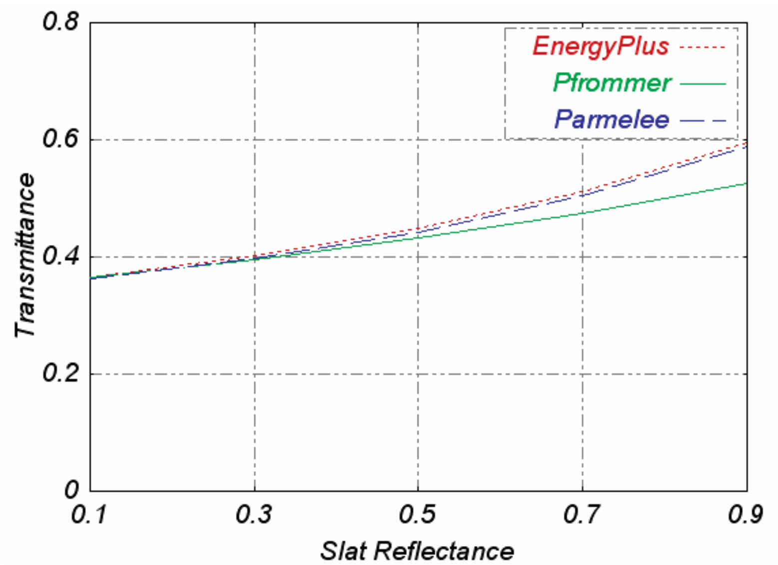


Figure 8-2 Transmittance through untilted blinds with flat slats with zero thickness, according to Chantrasrisalai and Fisher (2004).

8.3.2 Sunny skies

In this section the daylight transmittance through venetian blinds under three different sky conditions with sun and clear skies (scene 2, 5 and 8) is considered. For all daylight scenes and blind configurations considered, the blinds are adjusted to the sunlight cut-off tilt angle. When the sunlight cut-off tilt angle is negative, the blinds are kept in the untilted position. As indicated earlier, this allows for maximum horizontal view fraction, while also preventing direct sunlight from entering the interiors between the blind slats.

Different *S/W* ratios ranging from 0.6 to 0.9 are considered. The blind tilt at sunlight cut-off will depend on sun position and blind geometry according to equation 4.3. The blind tilt for the different clear sky scenes is given by Table 4-3.

It is of importance to keep in mind that tilting the blinds for sunlight cut-off is no guarantee for sufficient glare protection. This will be elaborated on in chapter 10.

For daylight scene 8, it is seen that the blind tilt at sunlight cut-off is negative for all spacing to width ratios. In the simulations the blinds are therefore kept untilted for this scene.

The daylight transmittance for the low sun scene (S2) is shown in Figure 8-3. It should be noted that the relative order of *S/W* with respect to daylight transmittance is reversed compared to that seen for overcast skies and untilted blinds. For the low sun scene the blind with the least overlap (*S/W* = 0.9) gives the least transmittance of all configurations. The reason for this is that more blind tilt is needed in order to achieve sunlight cut-off for this configuration. The increased blind tilt will limit the transmittance through the blinds, and the higher *S/W* cannot fully compensate for this.

Also, because of the substantial blind tilt needed for this low sun scene, the transmittance is strongly depending on the reflectance properties of the blind. For example; a slat reflectance of 0.5 gives a daylight transmittance of less than 0.15 for all *S/W* considered. Increasing the slat reflectance to 0.9 results in a transmittance between 0.3 and 0.4 for the *S/W* considered. Thus, the daylight supply is increased with more than 100%.

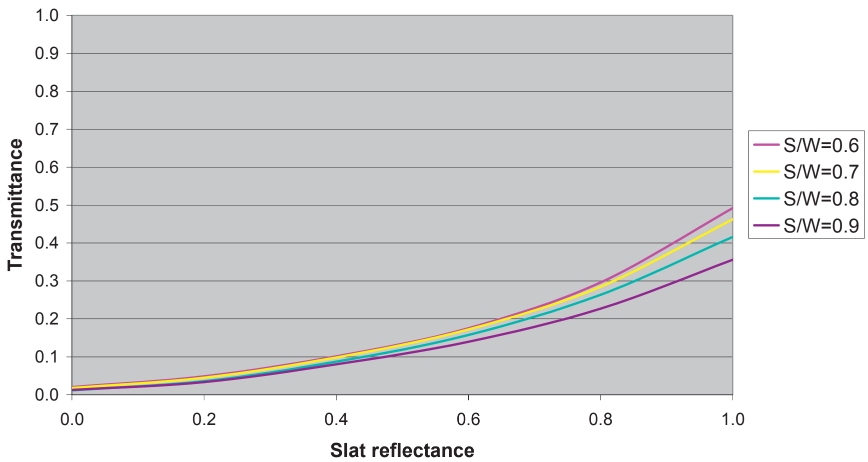


Figure 8-3 Transmittance through diffuse blinds tilted for sunlight cut-off in a low sun scene (S2).

The daylight transmittance for an intermediate sun scene (S5) is shown in Figure 8-4. Compared to the low sun scene, the blinds are less tilted, and the daylight transmittance is generally higher. The results show that the difference in transmittance is relatively small between the different *S/W* considered. This can be explained by two factors that work in the opposite direction: Increasing the spacing (*S/W)* leads to less multiple reflections at the slat surfaces, which increases the transmittance. But to prevent sunlight from entering the blinds with higher *S/W* need to be more tilted and this reduces the transmittance. The results indicate that these two effects more or less cancel each other for scene 5.

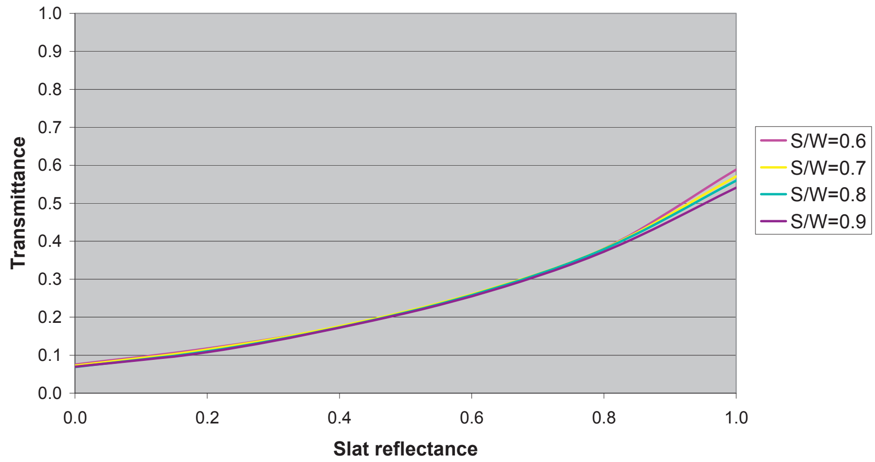


Figure 8-4 Transmittance through diffuse blinds tilted for sunlight cut-off in an intermediate sun scene (S5).

The daylight transmittance through diffuse untilted blinds for a high sun scene (S8) is shown in Figure 8-5.

The transmittance can be compared to that obtained under overcast sky, also for untilted blinds, as shown in Figure 8-1. For both scenes (overcast sky and high sun) the blinds with the highest *S/W* give the highest transmittance. Also, for both scenes the transmittance increases with increasing slat reflectance, as could be expected.

However, the transmittance values are generally lower for the high sun scene, especially for low slat reflectance. For the sunlight scene, a large percentage of the daylight, including all of the direct sunlight, is incident onto the slat surfaces and can only be transmitted after one or several reflections on the slat surfaces. This reduces the transmittance values, and emphasises the significance of the slat reflectance.

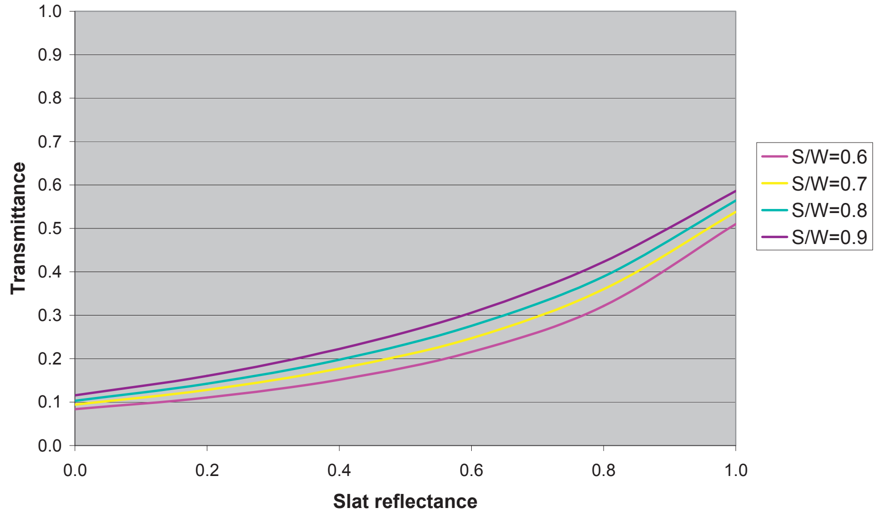


Figure 8-5 Transmittance through diffuse untilted blinds in a high sun scene (S8).

8.3.3 Conclusions for diffuse blind slats

The light transmittance through blinds with diffuse slats varies according to the angular distribution of incident light as defined by the daylight scene. For a given scene the transmittance varies with slat reflectance, slat tilting and spacing to width ratio (*S/W*).

As can be expected, the transmittance always increases with increasing slat reflectance. Under sunlight conditions, where most of the light is transmitted only after one or multiple reflections on the slat surfaces, the slat reflectance is of high importance. Under overcast sky conditions, where a large portion of the incident light passes through between the blind slats, the slat reflectance is of somewhat less importance.

For blinds tilted at a given tilt angle (for example $\beta = 0^{o}$ or $\beta = 45^{o}$) the blinds with the highest *S/W* provide the highest transmittance. This applies both under overcast sky and for sunny sky conditions. This result is quite natural, as the blinds with higher *S/W* are more "open". However, when the blinds are tilted for sunlight cut-off this picture can be altered. For scene 2 (low sun) the blinds with the smallest S/W provide the highest transmittance. This can be explained by the lesser tilt angle needed to assure sunlight cut-off for small *S/W*. For scene 5 (intermediate sun) the transmittance when the blinds are tilted for sunlight cut-off is practically the same for all the four *S/W* considered. Apparently, the two effects (openness and tilting) more or less cancel each other for this daylight condition.

8.4 Specular blind slats

In this section blinds with slats that are specular on both sides are considered. Such blinds are not very common since they might cause glare from double specular reflections. Yet, some examples of transmittance properties for such blinds are provided below.

As before, the simulations are also here carried out for flat blinds with zero thickness, and the blinds are positioned on the interior side of a double glazing. The transmittance results are also here corrected for the transmittance of the double glazing unit (as given in Table 8-1). This means that with perfectly transmitting blinds, the transmittance will be equal to 1. It also means that the actual transmittance values for double glazing units with interior blinds are lower than the values presented below.

8.4.1 Overcast sky

The transmittance through interior blinds in overcast sky conditions is shown in Figure 8-6. Compared to the results from diffusely reflective blinds in overcast sky, the transmittance with specular blinds is higher, especially for high slat reflectance. As the slat reflectance approaches 1, the transmittance through the untilted blinds approaches 100%. For diffuse blinds with a slat reflectance of 1 the transmittance was much lower, approximately from 60% to 70% as shown in Figure 8-1.

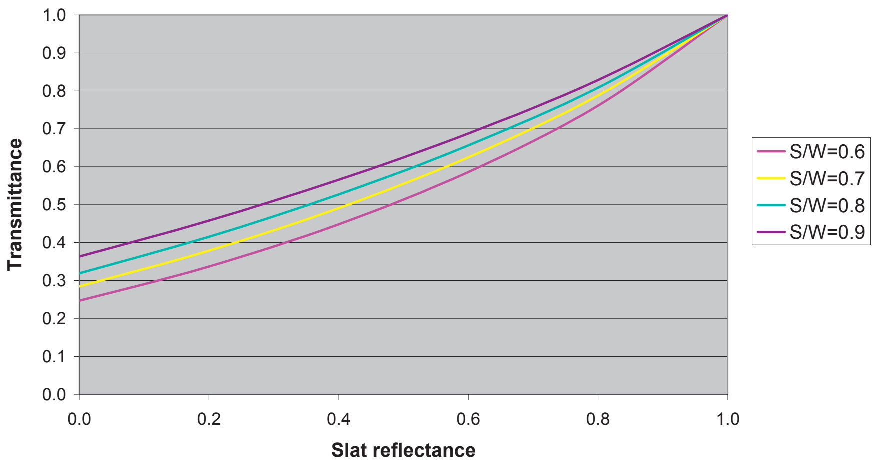


Figure 8-6 Transmittance through untilted blinds with flat specularly reflecting slats of zero thickness under overcast sky conditions (S1).

8.4.2 Low sun

The transmittance under low sun conditions (S2) for blinds tilted for sunlight cut-off is shown in Figure 8-7. The results show that the blind with *S/W* of 0.9 gives the lowest transmittance. One important reason for this is that the blind tilt is here so large that a significant fraction of the direct sunlight is reflected back towards the window panes and will not pass through the blinds and into the interiors.

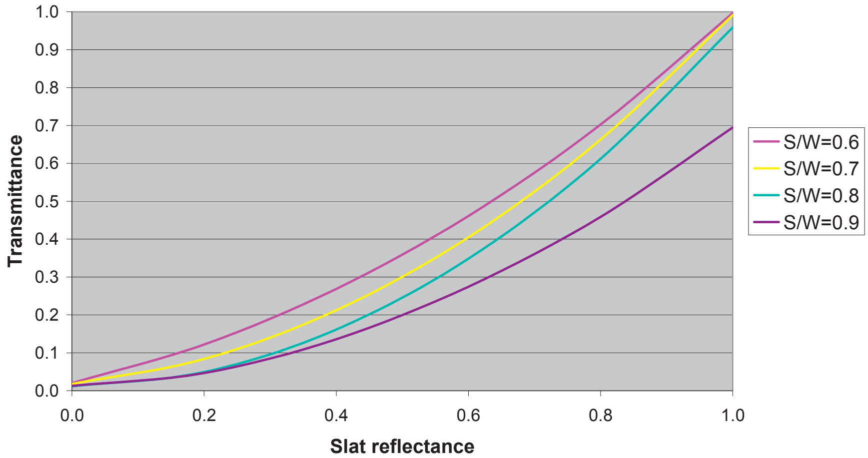


Figure 8-7 Transmittance through blinds with flat specularly reflecting slats tilted for sunlight cut-off in a low sun scene (S2).

8.4.3 Conclusions for specular blind slats

The results for overcast sky and low sun indicate the daylight supplying potential of blinds with slats that are specularly reflective. Compared to diffusely reflective (white) blinds, the results show that the transmittance properties of specularly reflective blinds can be very good provided that the slats are highly reflective.

The next question to be addressed is what happens when the lower side of the slats is diffuse (grey) and only the upper side is specular. This is considered in the next section.

8.5 Slats with a grey lower side

Blinds that are specular and highly reflective on both sides can be problematic with respect to glare performance. Specular blinds are therefore often provided with a diffuse grey surface on the lower side.

In this section blinds with flat slats that are dark grey on the lower side is considered. The grey side is diffusely reflective with a reflectance of 0.2. Note that this is lower than for the “reflective” blind simulated in chapter 6, where a light grey lower side with a diffuse reflectance of 0.4 was considered.

In this section most of the simulations have been done on slats where the upper side is specular, but some results for blinds with diffuse reflectance on the upper side are also included.

As for the previous sections in this chapter, the simulations are also here carried out for flat blinds with zero thickness, and the blinds are positioned on the interior side of a double glazing.

8.5.1 Overcast sky

Simulation results for overcast sky are provided in Figure 8-8. The graph shows transmittance values for blinds that are specular or diffuse (lambertian) on both sides as well as both specular and diffuse blinds provided with a dark grey lower side.

As expected, the blind that is specular on both sides give the highest daylight transmittance for overcast sky conditions. Adding a dark grey finish to the lower side of the slats reduces the transmittance with up to 30%.

The blind that is specular on the upper side and dark grey on the lower side gives a higher daylight transmittance than the blind that is diffuse on both sides.

The lowest daylight transmittance is obtained with the blind that combines a diffuse upper side with a dark grey lower side.

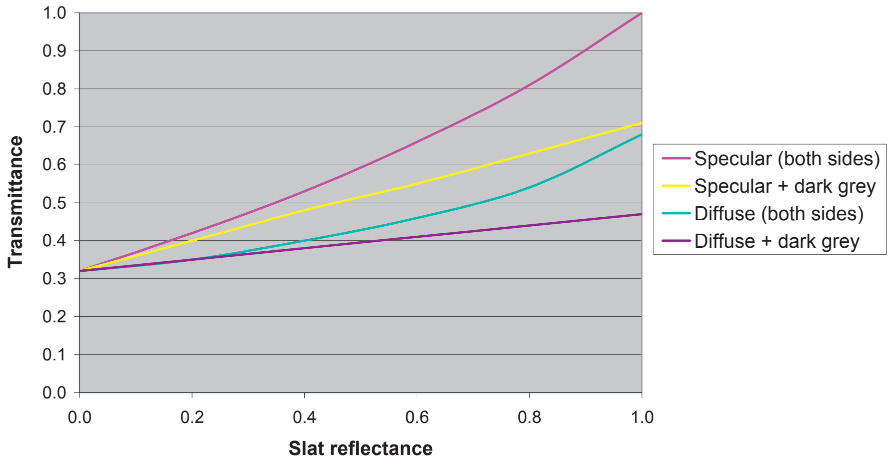


Figure 8-8 Transmittance through untilted blinds with S/W = 0.8 under overcast sky conditions (S1). For the blinds that are specular or diffuse on both sides the given slat reflectance is the same for both sides of the slat. For the slats with a dark grey lower side the reflectance of the lower side is kept constant at 0.2.

8.5.2 Conclusions for slats with a grey lower side

The results show that a dark grey surface on the lower side of the slats reduces the light transmittance through the blinds significantly. This applies both when the upper side is specular as well as diffuse. Still, a grey lower side is often used in practice, in particular so for reflective blinds. The reason for applying a grey surface on the lower side is to provide better glare protection. Glare from windows will be discussed further in chapter 10.

8.6 Light transmittance for selected blind configurations

In chapter 7 the illuminance distributions in a sidelighted space was presented for several different blind types and tilt angles, and for different daylight scenes. The results in chapter 7 showed that the blind type and blind tilting has a large impact on the resulting illuminance levels. The reflective blind tilted for daylight redirection generally gave higher illuminance levels, but not for all of the daylight scenes considered. It is therefore of interest to see if the light transmittance of the respective blind types reflects the differences found in the illuminance distributions.

In the following sections the light transmittance under daylight scenes 1 to 10 is provided. The blind configurations are the same as those discussed in chapter 7.

Please note that in this section the given light transmittance values are for the whole fenestration system, and are therefore *not* corrected for the transmittance of the double glazing, unless this is explicitly stated.

As described earlier, the term “NB” (no blinds) refers to the situation with only a double glazing unit present.

The term “w” refers to a white blind with a diffuse slat reflectance of 0.70 on both sides and a spacing to width ratio of 0.9. The angle following the “w” specifies the tilt angle of the white blind. So, for example, the term “w45º” refers to a white blind tilted with a tilt angle (β) of 45º.

The term “r” refers to a reflective blind with a specular slat reflectance of 0.95 on the upper side and a diffuse slat reflectance of 0.4 (light grey) on the lower side. The spacing to width ratio of this blind is 0.6. The angle following the “r” specifies the tilt angle of the reflective blind, so, for example “r-20º” refers to a reflective blind tilted at -20º.

8.6.1 Overcast sky

The light transmittance values for selected systems under overcast sky conditions (S1) is given in Table 8-2. As expected, the highest light transmittance is provided by the configuration without any blinds present (NB). For the untilted blinds, the reflective blind provides a slightly higher transmittance than the white blind (0.46 compared to 0.40). The transmittance values of the different configurations seem to be in good agreement with the illuminance values obtained on the floor of the sidelighted space, as shown in Figure 7-1. For example, considering the low transmittance of the white blind tilted at 45º, it should come as no surprise that this blind configuration gives the lowest illuminance values when applied in a sidelighted space.

Table 8-2 Light transmittance for selected systems under overcast sky.

Scene	Blind configuration	Light transmittance
1	NB	0.74
1	w0º	0.40
1	w45º	0.21
1	r0º	0.46

8.6.2 High sun conditions

In this section the light transmittance of the selected systems under high sun conditions is discussed.

The light transmittance for scene 8 ($\Delta\alpha_s$ = 15º) is given in Table 8-3. Again, as expected, the configuration without blinds present provides the highest light transmittance. The reflective blind provides clearly superior light transmittance compared to the white blind; especially when the white blind is tilted at 45º. Again, the results seem to be in good qualitative agreement with the resulting illuminance levels in a sidelighted space, as given in Figure 7-3. For example, with closed blinds in the view opening, the configuration with untilted white blinds in the daylight opening (CB + w0º) provides significantly lower illuminance levels compared to applying a reflective blind in the daylight opening (CB + r-20º).

The light transmittance for scene 9 ($\Delta\alpha_s$ = 45º) is given in Table 8-4. The calculated light transmittance values for the white blinds are very similar to those obtained for scene 8. The reflective blind is not quite as superior with respect to light transmittance, but still significantly better than the white blind. The similarity in transmittance values between scene 8 and scene 9 is mirrored in the similarity between the floor illuminance levels for the two scenes; as given in Figure 7-3 and Figure 7-5.

The light transmittance for scene 10 ($\Delta\alpha_s$ = 75º) is given in Table 8-5. Here the situation has radically changed! For this scene, the light transmittance of the reflective blind is much lower than for scene 8 and 9, and comparable to the transmittance of the white blind tilted at 45º. This reflects the results obtained for floor illuminance as seen in Figure 7-7. For this particular high sun scene, the reflective blind does not provide higher floor illuminance levels than the white blind. As discussed earlier, the reason for this is that a large fraction of the light that is reflected off a slat is directed towards the overlying slat and not (directly) into the interiors.

Table 8-3 Light transmittance for selected systems under high sun (S8).

Scene	Blind configuration	Light transmittance
8	NB	0.79
8	w0º	0.28
8	w45º	0.18
8	r-20º	0.67

Table 8-4 Light transmittance for selected systems under high sun (S9).

Scene	Blind configuration	Light transmittance
9	NB	0.70
9	w0°	0.26
9	w45°	0.17
9	r-25°	0.56

Table 8-5 Light transmittance for selected systems under high sun (S10).

Scene	Blind configuration	Light transmittance
10	NB	0.54
10	w0°	0.28
10	w45°	0.20
10	r-35°	0.21

8.6.3 Intermediate sun conditions

In this section the light transmittance of the selected systems under intermediate sun conditions is discussed.

The transmittance values for intermediate sun conditions shown in the following tables are comparable to those obtained for high sun conditions. This corresponds well with the results for floor illuminance obtained in chapter 7. Also here, the floor illuminance of intermediate sun and high sun are comparable.

One notable difference is that the light transmittance of the reflective blind is higher for intermediate sun conditions. For scene 6 and 7 the transmittance is 0.69 and 0.34, while for the corresponding high sun scenes (scene 9 and 10) the transmittance is 0.56 and 0.21 respectively. The reason for this is that, for intermediate sun conditions, a smaller fraction of the incident sunlight is reflected off a slat towards the overlying slat.

Table 8-6 Light transmittance for selected systems under intermediate sun (S5).

Scene	Blind configuration	Light transmittance
5	NB	0.83
5	w20.7°	0.26
5	w45°	0.18
5	r1.1°	0.72

Table 8-7 Light transmittance for selected systems under intermediate sun (S6).

Scene	Blind configuration	Light transmittance
6	NB	0.78
6	w6.0º	0.29
6	w45º	0.17
6	r-10.5º	0.69

Table 8-8 Light transmittance for selected systems under intermediate sun (S7).

Scene	Blind configuration	Light transmittance
7	NB	0.54
7	w0º	0.25
7	w45º	0.16
7	r-30º	0.34

8.6.4 Low sun conditions

In this section the light transmittance of the selected systems under low sun conditions is discussed.

The results in the following tables show that the reflective blind here provides significantly higher light transmittance values than the white blind. This corresponds to the results for floor illuminance for low sun in chapter 7, where the reflective blind generally provides higher floor illuminance levels than the white blind.

Although the reflective blind provides relatively high transmittance values compared to the white blinds, the transmittance obtained for scenes 2 and 3 are still relatively low compared to the situation without blinds. For scene 2 the reflective blind reduces the transmittance from 0.84 (without blinds) to 0.43. For scene 3 the reflective blind reduces the transmittance from 0.81 to 0.46. From this point of view, the reflective blind show a relatively poor performance for scene 2 and 3.

Table 8-9 Light transmittance for selected systems under low sun (S2).

Scene	Blind configuration	Light transmittance
2	NB	0.84
2	w53.0º	0.15
2	r26.8º	0.43

Table 8-10 Light transmittance for selected systems under low sun (S3).

Scene	Blind configuration	Light transmittance
3	NB	0.81
3	w47.8º	0.16
3	r22.6º	0.46

Table 8-11 Light transmittance for selected systems under low sun (S4).

Scene	Blind configuration	Light transmittance
4	NB	0.53
4	w14.8º	0.20
4	w45º	0.12
4	r-3.5º	0.45

8.6.5 Transmittance versus projected solar elevation

The results show that the reflective blind generally provides higher transmittance values than the white blind. The scenes that reduce the transmittance values the most with reflective blinds (compared to the transmittance of the double glazing without blinds) are scenes 2, 3, 7 and 10. It is interesting to observe that these scenes are the scenes with the two *lowest* and two *highest* projected solar elevations.

It is therefore of interest to take a closer look at the transmittance of the different blind types as a function of the projected solar elevation angle. The values obtained from the TracePro simulations are plotted in Figure 8-9. The transmittance values provided here are adjusted for the transmittance of the double glazing unit.

The tilt angles for the respective blind types are the same as those considered above and the reasons for the tilt angles considered are explained in detail in chapter 7; see Table 7-1.

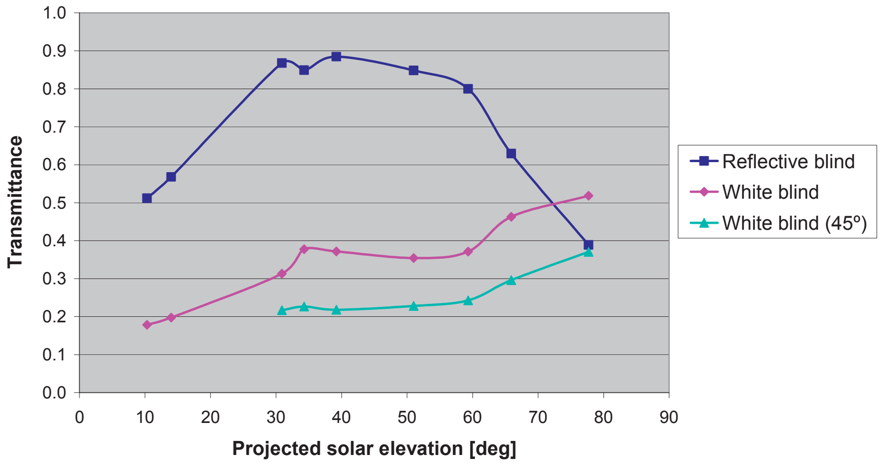


Figure 8-9 Light transmittance as a function of projected solar elevation angle for different blind types.

The results show that the reflective blind provides superior light transmittance properties compared to the white blinds for all scenes considered except for scene 10; the scene with the highest projected solar elevation.

The reason behind this interesting result can be understood by taking a closer look at the ray paths through the blind system. Following from a ray trace; TracePro can provide a graphical visualisation of the ray paths through the blinds. By studying the ray paths the reason for the low light transmittance becomes apparent: As can be seen in Figure 8-10, both for high sun scenes and for low sun scenes most of the rays specularly reflected off one slat are directed towards the lower side of the overlying slat. Here, at the grey surface, the light is diffusely reflected and partly absorbed.

For high projected solar elevation angles the reason for this lies in the high angle of incidence of direct sunlight, combined with the need to limit the downward (negative) tilting of the blinds so as to avoid downward directed specular reflections. If downward directed reflections were allowed, the transmittance could here be increased.

For low projected solar elevations the reason lies in the need to tilt the blinds substantially (positive tilt) so as to obtain sunlight cut-off. If direct sunlight was allowed to pass between the slats, the transmittance could also here be increased.

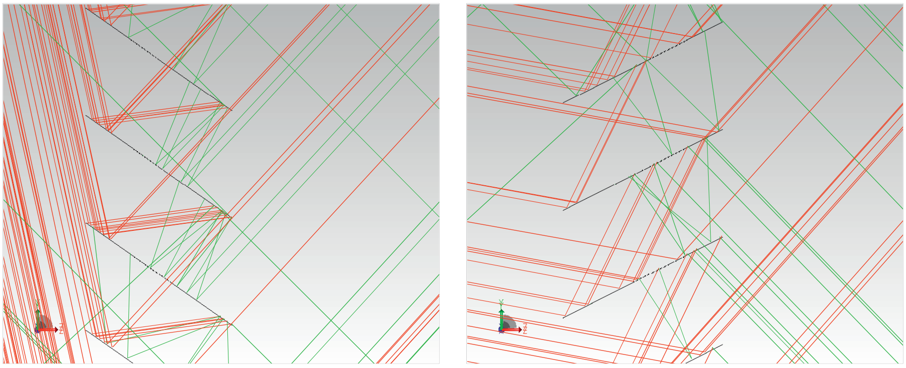


Figure 8-10 Ray paths for the reflective blind system. Left: High sun (scene 10). Right: Low sun (scene 2). Rays are incident from the left. A red colour indicates rays with high flux. A green colour indicates rays with reduced flux due to diffuse reflections at the lower grey slat surface. Only a small fraction of the traced rays are shown, and rays with low flux due to multiple diffuse reflections are omitted.

A larger spacing to width ratio (*S/W*) of the reflective blind would enable higher transmittance values at *high* projected solar elevations (scenes 7 and 10). However, this would make the transmittance even lower under *low* sun conditions (scene 2 and 3). From this it can be concluded that the spacing to width ratio under consideration (*S/W* = 0.6) is a reasonably good choice for high latitudes, with respect to obtaining high light transmittance values for most of the relevant sun positions.

Here it should also be emphasised that most blinds are slightly curved. For reflective (daylight redirecting) blinds the best results are obtained with a concave curvature, as illustrated in section 3.3.1. With a slightly concave slat curvature, the light that is incident on the outer parts of the slats will be reflected at a lower angle. For high sun, where the incident light only reaches the outer parts of the slats, less light will be directed towards the lower side of the overlying slat. A slightly concave slat curvature will therefore increase the transmittance of the reflective blind for high sun scenes.

8.7 Summary and conclusions

The light transmittance through daylighting systems with double glazing and interior venetian blinds has been studied. The results presented in this chapter show that the light transmittance depends on several factors; (i) the angular distribution of incident light as given by the different daylight conditions, (ii) the properties of the blinds; including the slat reflectance properties and the spacing to width ratio, and (iii) the tilt angle of the blind slats.

The results show that blinds with specularly reflective slats have the potential to provide superior transmittance properties. However, the superior transmittance values are only obtained for a limited range of projected solar elevation angles. The reason for this is that there are restrains to the tilt angle allowed due to the desire to avoid direct sunlight and downward directed specular reflections within the interiors.

The results illustrated in Figure 8-9 show that the transmittance of the considered reflective blind peaks for projected solar elevation angles in the region from 30º to 60º. This result indicates that the spacing to width ratio of 0.6, as considered here, is an appropriate choice for maximising light transmittance under sunlight conditions that are typical for high latitudes.

The light transmittance of a system under a particular daylight scene is given by the properties of the daylighting system itself; and is not influenced by the properties of the actual room where the system is applied. It is therefore not to be expected that the light transmittance of a daylighting system can be used to quantify the absolute illuminance levels of a space.

Still, the results show that for a given sidelighted space, the light transmittance of a system correlates reasonably well with the actual illuminance levels obtained from applying the system. So in this respect, the light transmittance can be used as a good indicator for the *relative performance* of different systems.

However, the illuminance levels in a space are not only determined by the *quantity* of light, but also by how this light is *distributed* within the interiors. The distribution of light transmitted through daylighting systems is the subject of the next chapter.

9 Luminous intensity distributions

I'm afraid of the dark, and suspicious of the light.

Woody Allen

9.1 Introduction

In the previous chapter the light transmittance for various venetian blind systems under different daylight conditions were studied. The daylight transmittance is clearly an important quantity that provides information about the ability of the blind systems to supply daylight to the interiors. However, the transmittance does not provide any indication about the distribution of the transmitted light.

In this chapter the luminous intensity distributions of the transmitted light are studied. Luminous intensity plots (also called candela-plots) are frequently used in the design and specification of illumination systems, especially those used for interior lighting in buildings. Until now, such plots have only had a limited use in the specification of daylighting systems but this might change following from the development of advanced computer simulation tools that makes it much less elaborate to obtain the luminous intensity distributions.

In the following sections luminous intensity distributions of various venetian blind systems operating under various daylight scenes will be given. Furthermore, the usefulness of the luminous intensity distributions in providing important information about the system will be discussed.

9.2 Candela plots in TracePro

In TracePro it is possible to generate so-called polar candela plots that give information about the luminous intensity distribution resulting from a ray trace. A polar candela plot shows the spherical polar angle on the polar axis, and a spherical azimuth angle in the azimuth direction. Note that the azimuth direction is here relative to the polar axis of the plot, and should not be confused with the azimuth direction of the sun or sky as defined by Figure 4-1. The polar candela plot maps a hemisphere onto a plane.

9.2.1 Candela plot for the overcast sky

An example might better explain how to interpret the candela plot. The plot given in Figure 9-1 is obtained from the simulations of daylight through the upper daylight opening of the reference room for overcast sky conditions (S1). No glazing or daylighting components are present.

The polar axis in the plot has been defined to be parallel with the direction vector of the window opening, but pointing towards the interior. The centre of the candela plot will then represent that direction, and the value at the centre of the plot therefore gives the luminous intensity in the z-direction (as defined in Figure 4-6).

The azimuth angles of the plot go from 0º to 360º. An azimuth angle of 0º indicates an upward direction (along the positive y-axis), and 180º indicates a downward direction.

The values to be found on the upper semi-circle, above the dotted line are from light directed upwards. Here the azimuth angle is from 0º to 90º or from 270º to 360º. For the example in Figure 9-1 the values above the dotted line originate from ground reflected light. As can be expected, the candela values in this region are relatively low.

The values found on the lower semi-circle (below the dotted black line) are from light directed downwards. Here the azimuth angle is from 90º to 270º. For the example in Figure 9-1 the values below the dotted line originate from the overcast sky. As can be expected, the values on the lower semi-circle are higher than the values on the upper semi-circle.

The polar angles of the plot go from 0º to 90º. Polar angles of 25º, 50º and 75º are indicated by numbers within the plot. The polar angle of a point in the plot quantifies the direction angle relative to the z-direction. The dotted black circle indicates all directions that are 45º away from the z-direction. Depending on the azimuth angle, the direction can be upwards (azimuth = 0º), downwards (azimuth = 180º) or sideways (azimuth = 90º or 270º).

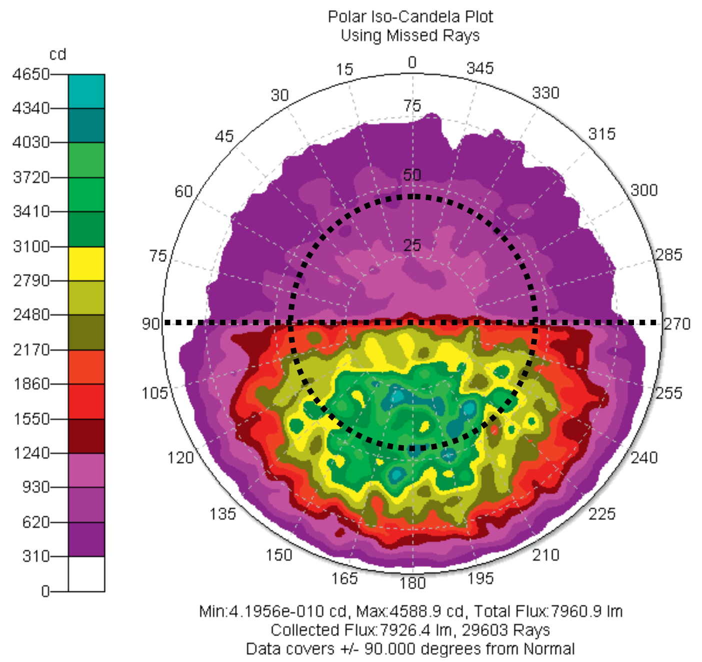


Figure 9-1 Candela plot for daylight through the upper daylight opening of the reference room for overcast sky conditions (S1). No glazing or daylighting components are present.

9.2.2 Candela plots for the clear sky scenes

In this section the candela plots for daylight entering through the daylight opening of the reference room are shown. The plots indicate the luminous intensity distribution on a logarithmic scale resulting from the different clear sky scenes (summarised in Table 5-1) without any glazing or fenestration system present. The luminous intensity from the sun can be seen as a small blue dot in the plots. As expected for the clear skies, the angular region close to the direction of the sun gives the highest luminous intensity. These plots provide a good indication that the light distributions given by the TracePro ray files are in accordance with the mathematical sky models from which they are derived.

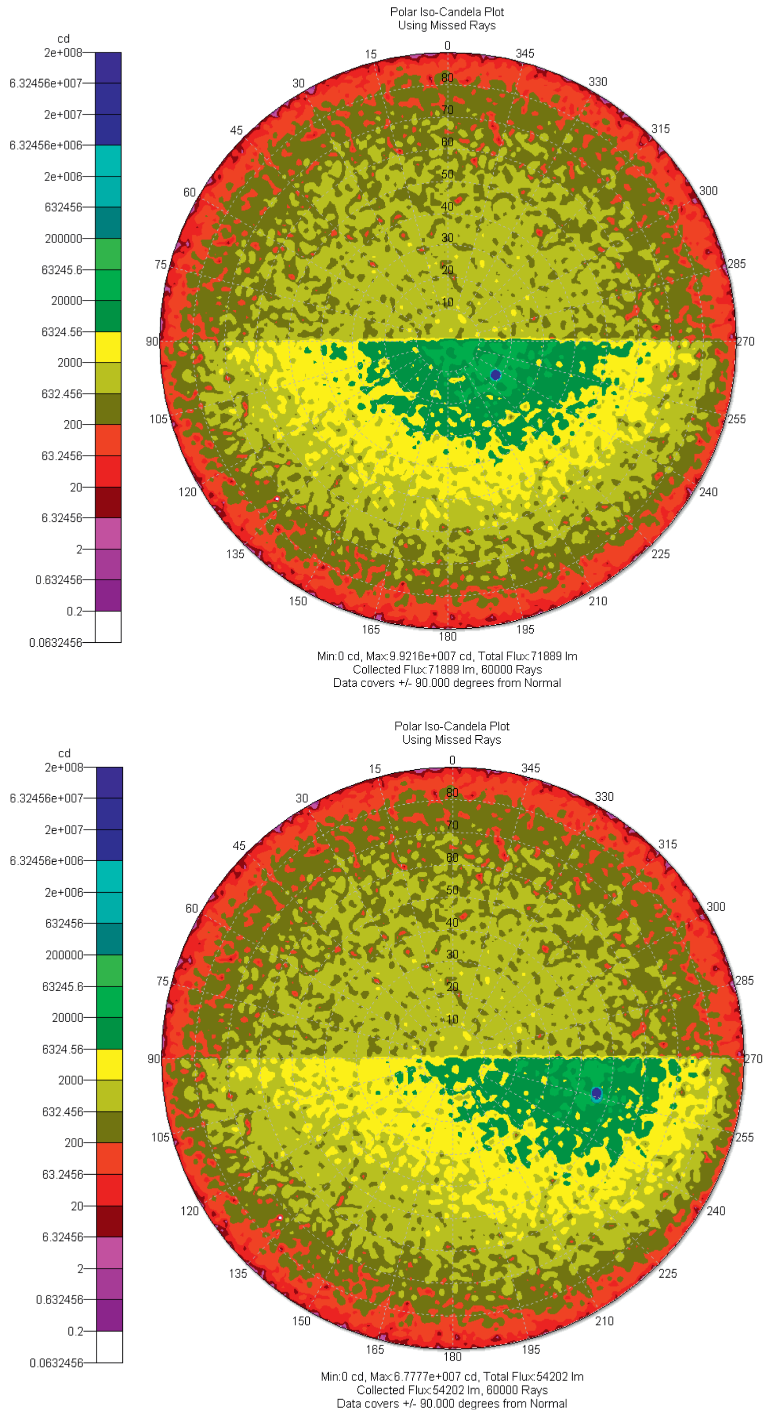


Figure 9-2 Candela plot for daylight scene 2 (above) and 3 (below).

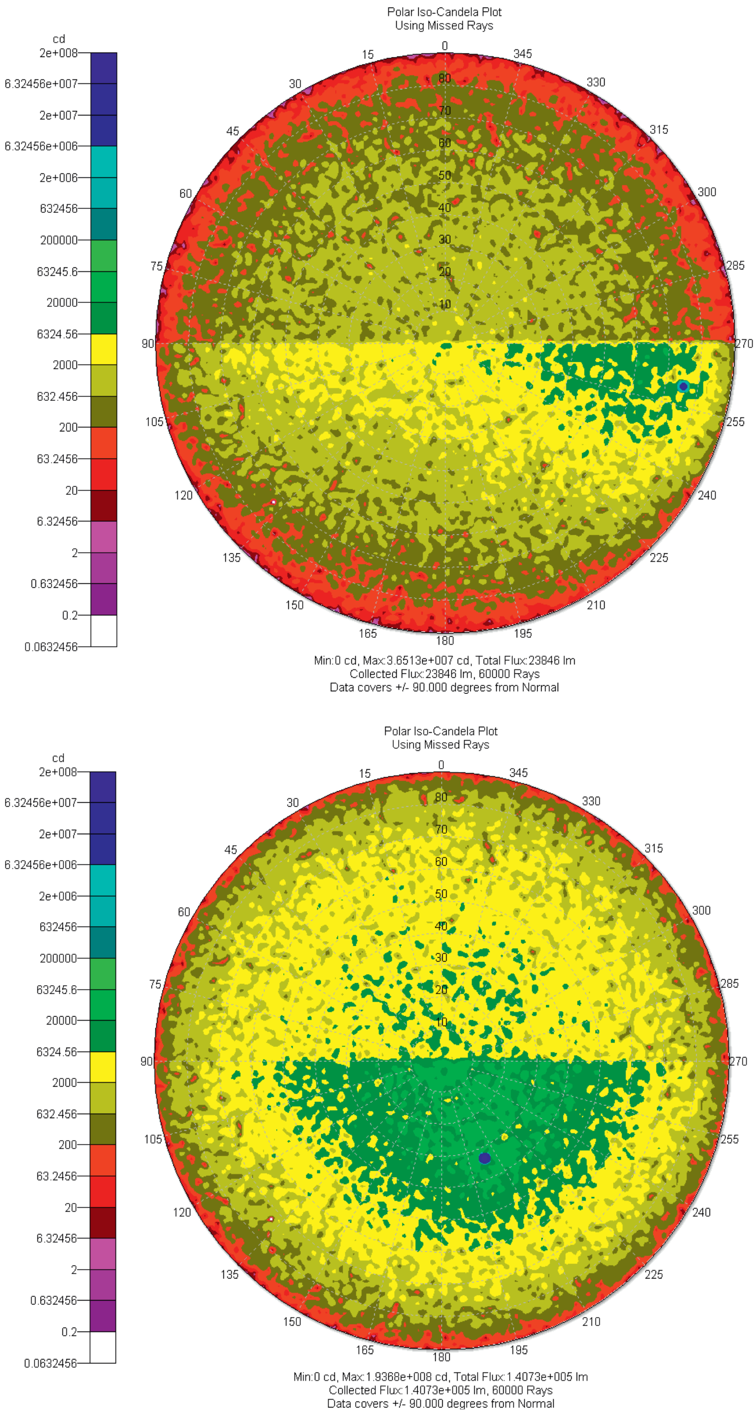


Figure 9-3 Candela plot for daylight scene 4 (above) and 5 (below).

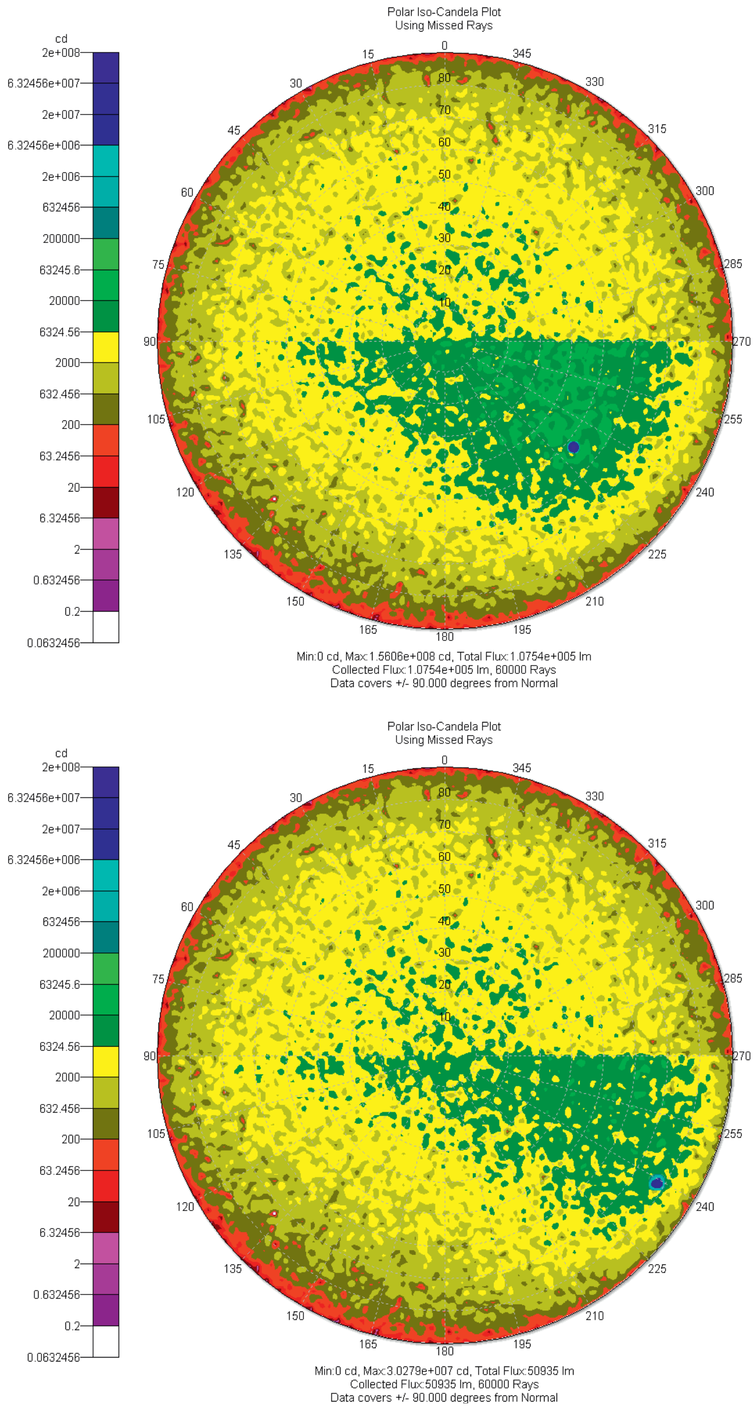


Figure 9-4 Candela plot for daylight scene 6 (above) and 7 (below).

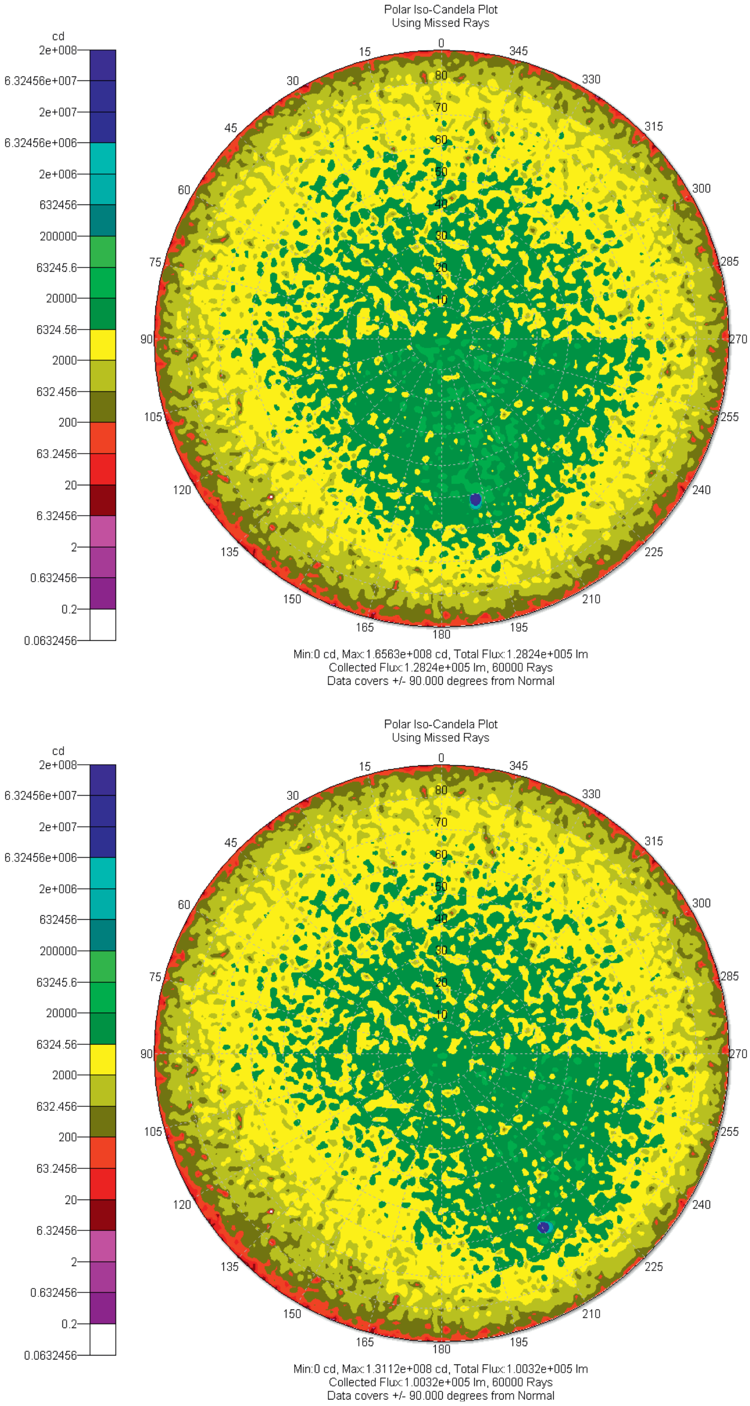


Figure 9-5 Candela plot for daylight scene 8 (above) and 9 (below).

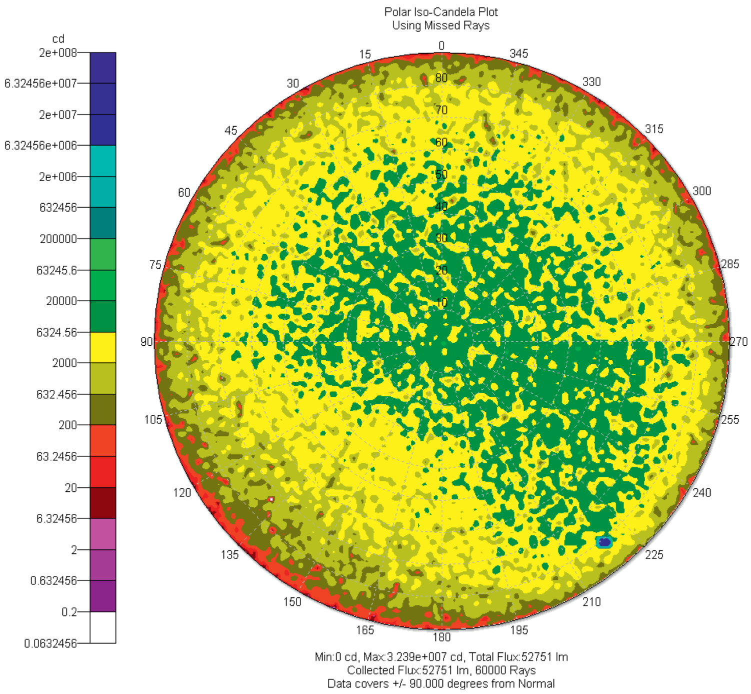


Figure 9-6 Candela plot for daylight scene 10.

As could be expected, the candela plots for clear skies show that most of the light that enters the interiors undisturbed is directed downwards. The direction with the highest luminous intensity is the direction of light from the sun. But also the diffuse light originating from regions near the sun provide high luminous intensities. The luminous intensities in the upward directions are generally much lower.

These plots can be used to explain why the luminances on the floor (or side walls) from a window opening (without any daylighting or shading components) are generally much higher than on the ceiling; particularly for the areas exposed to direct sunlight.

The interesting question is what happens to the candela plots when blinds (and double window panes) are introduced in the window openings. A few examples of such plots are therefore provided in the following sections.

9.2.3 Candela plots with venetian blinds

Candela plots for scene 5 (intermediate sun) and 8 (high sun) are provided for different blind configurations. For both of these scenes the azimuth (difference) angle relative to the window normal ($\Delta\alpha_s$) is 15º.

Blinds that cover the entire window opening are introduced. This includes diffuse white blinds (ρ = 0.7) with different slat tilts as well as reflective blinds with specular upper surface (ρ = 0.95) and a grey lower side (ρ = 0.4). For the white blind the spacing to width ratio (*S/W*) is 0.9, and for the reflective blind it is 0.6.Also, for all the plots a double glazing unit is also included in the simulations.

As can be expected, the regions with the highest luminous intensity are now generally found for upward directions; that is, in the upper half of the plots.

With diffusely reflecting (white) blinds, the upward distributions are symmetric about the z-direction. For the reflective blind the distributions are slightly asymmetric, mirroring the asymmetry ($\Delta\alpha_s$ = 15º) of the incident daylight distribution.

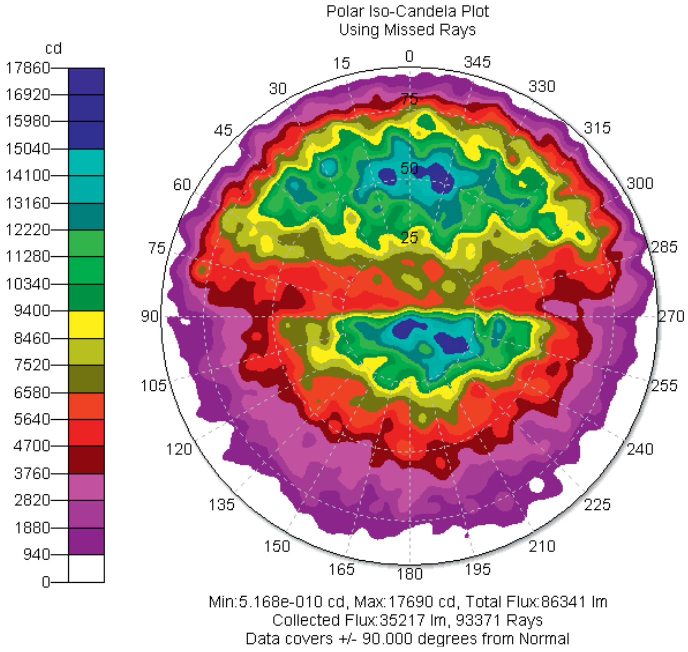


Figure 9-7 Candela plot for scene 5 with diffuse white blinds (ρ = 0.7, *S/W* = 0.9) with slats tilted for sunlight cut-off (β = 20.71º).

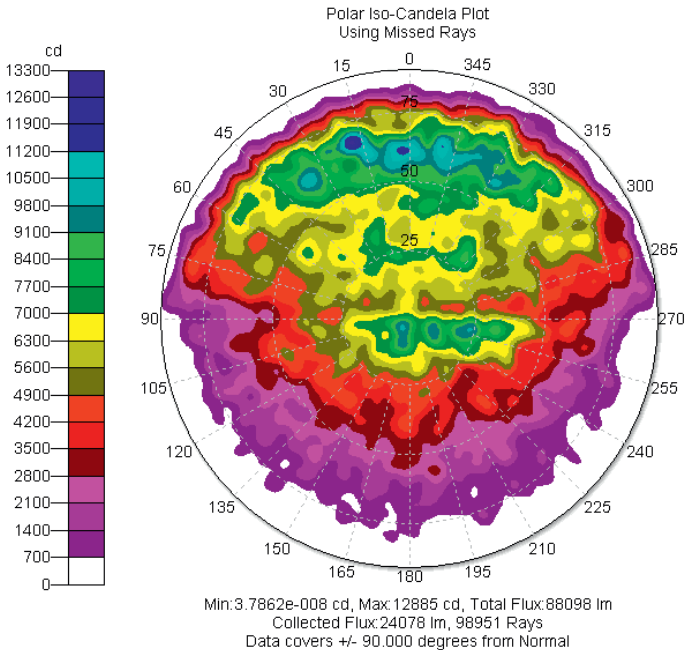


Figure 9-8 Candela plot for scene 5 with diffuse white blinds (ρ = 0.7, *S/W* = 0.9) with slats tilted 45º.

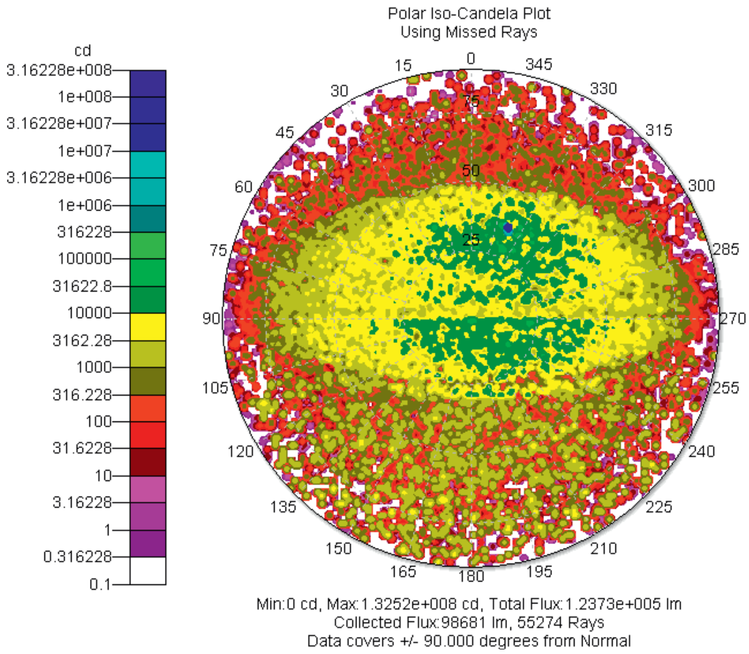


Figure 9-9 Candela plot for scene 5 with a reflective blind with specular upper surface (ρ = 0.95) and a grey lower side (ρ = 0.4). *S/W* = 0.6 and the slats are tilted for sunlight cut-off (β = 1.13º). The plot scale is logarithmic to better represent the high luminous intensity from the specular reflection of sunlight (blue dot), as well as the diffuse components to the flux.

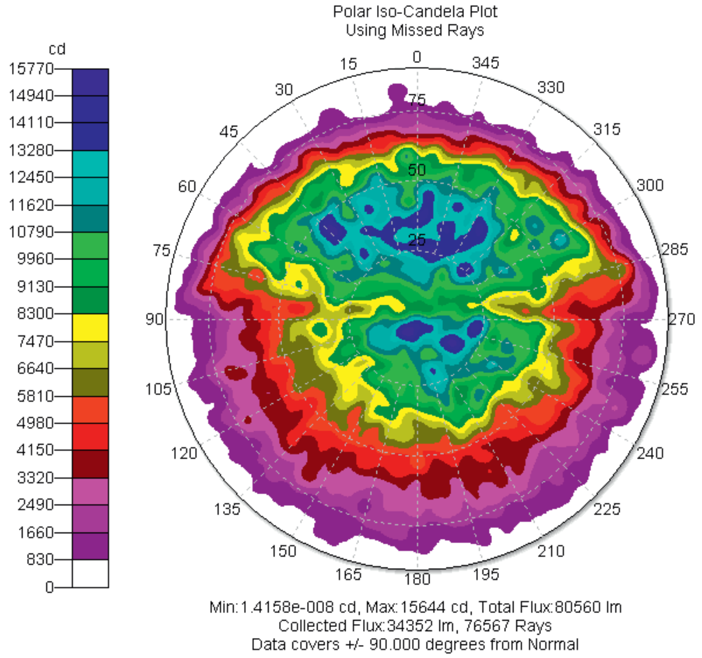


Figure 9-10 Candela plot for scene 8 with diffuse white blinds (ρ = 0.7, *S/W* = 0.9) with untilted slats (β = 0º).

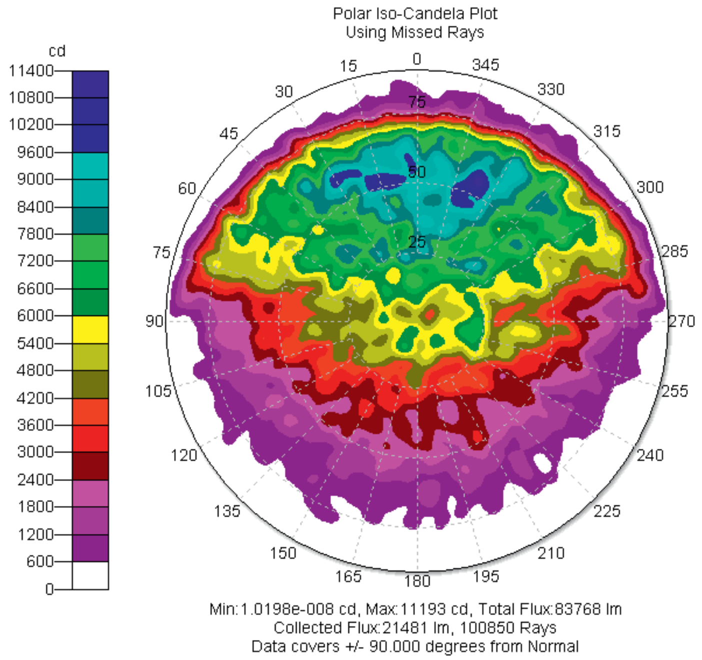


Figure 9-11 Candela plot for scene 8 with diffuse white blinds (ρ = 0.7, *S/W* = 0.9) with slats tilted 45º.

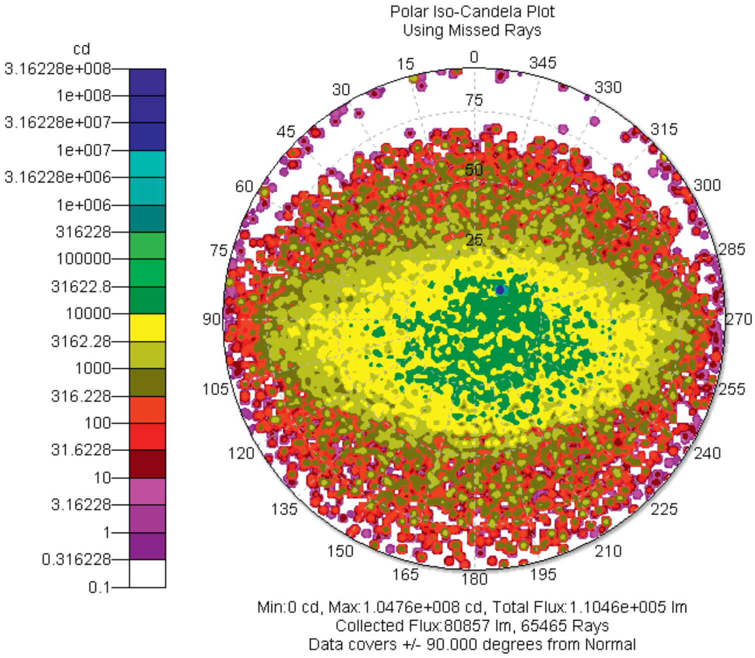


Figure 9-12 Candela plot for scene 8 with a reflective blind with specular upper surface (ρ = 0.95) and a grey lower side (ρ = 0.4). *S/W* = 0.6 and the slats are tilted to redirect sunlight upwards (β = -20º). Due to the high luminous intensity from the specular reflection of sunlight (blue dot), the plot scale is logarithmic.

9.3 Light distribution histograms

The luminous intensity distributions provided by a simulation in TracePro contain a lot of useful information that might not be immediately apparent from the candela plots discussed in the previous section.

For example, suppose that one is interested in knowing the fractions of the total transmitted light that is directed upwards and downwards. This can be obtained by analysing the luminous intensity distributions. One option is to export the data from TracePro and import them for analysis in a spreadsheet or other program. But TracePro also allows the user to define angular regions of interest and can then provide values for the enclosed flux in that particular region.

It is here proposed to divide the light passing through the fenestration system into 4 angular regions, as illustrated in Figure 9-13. The first angular region of interest is the downward directed light. Since skylight comes from the upper hemisphere, most light entering through a window opening (without shading or daylighting components) will be directed downwards. This often creates a situation where the ceiling is darker than the rest of the interiors, especially at locations far away from the window facade, as shown for the sidelighted space discussed in chapter 7. This type of light distribution can make the room appear gloomy. One of the main benefits of daylight redirection systems is to brighten the ceiling and prevent a gloomy appearance. For this to be successful, a large fraction of the light entering the space needs to be directed in the upward direction. However, light directed upwards will not necessarily reach the deeper interiors of a space. For this to apply, the light must be oriented in a direction that is close to that of the window normal.

It is therefore proposed to divide the upward directed light into three categories defined by the angle of the light relative to the window normal (z-direction). When the angle is in the interval 0º-30º, the light is assumed to reach the middle locations of the room as well as the deeper interiors. When the angle is in the interval 30º-60º, the light is assumed to be directed towards the window zone and the middle locations, and when the angle is in the interval 60º-90º, the light is assumed to contribute mostly to locations near the window opening. Note that the locations reached for the different categories will be overlapping due to the extended area of the daylight opening.

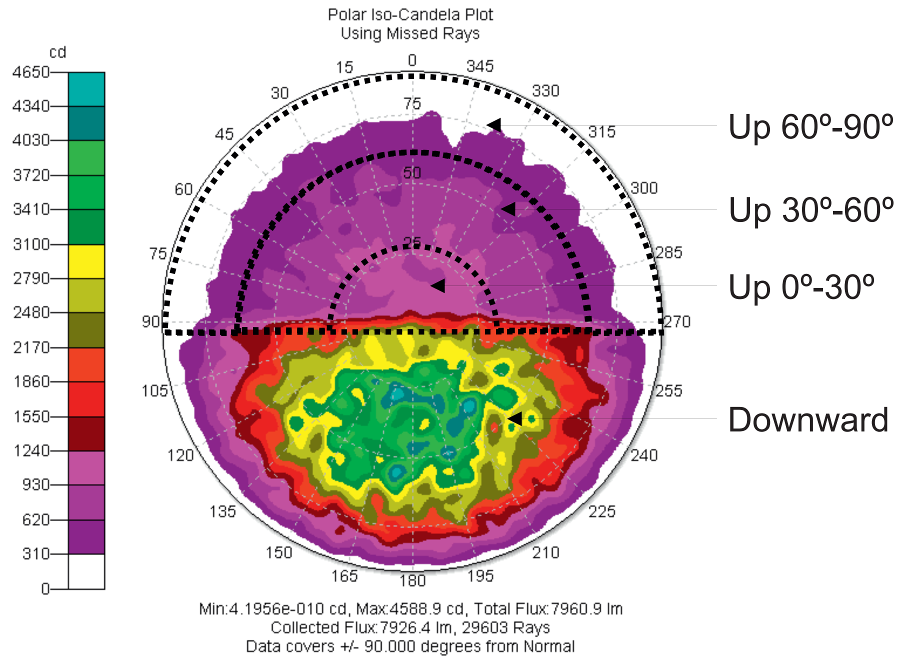


Figure 9-13 The distribution of incoming light can be categorised by the introduction of 4 angular regions. In this situation (overcast sky with glazing only) most of the light is directed in the downward angular region.

Naturally, the exact destination of the light entering through the daylighting system will depend on the geometry of the space and the positioning and size of the daylight openings. However, for the typical sidelighted space it seems reasonable to assume that the light directed upwards with a direction lying in the interval 0º-30º from the z-direction will contribute the most in providing daylight to the middle and deeper parts of the interior space, and thus contribute the most in preventing the room from appearing gloomy.

It should be remarked that the following light distribution histograms are normalised to the total transmitted flux, and therefore do not provide any information about the actual *amount* of light transmitted towards the different regions. To obtain information about the total transmitted flux for each histogram, the light transmittance values provided in the previous chapter should be taken into account.

9.3.1 Double window glazing

The double window glazing only slightly alters the distribution of the daylight that is transmitted through the window (compared to an empty window opening). It is well known from the literature that the illuminance distribution in a sidelighted space is generally quite uneven, with most of the diffuse light directed towards the floor area near the window. This is also confirmed by the TracePro simulations for overcast sky conditions shown in Figure 6-3.

The light distribution histograms for a double glazing unit without any additional daylighting or shading systems shown in Figure 9-14 also exemplify this. For all of the daylight scenes considered, the downward directed light is dominating, and the amount of light in the Up 0-30 direction is relatively small. For all of the scenes except 1, 7 and 10, the fraction of flux in the Up 0-30 direction is less than 5% of the total transmitted flux.

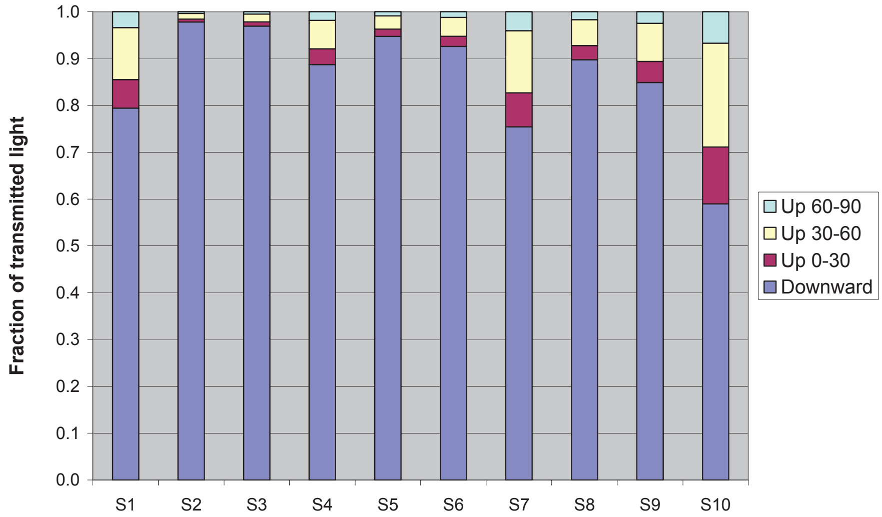


Figure 9-14 Light distribution histograms for a double window glazing under different daylight scenes.

9.3.2 Overcast sky

In this and the following sections the effect of white or reflective blinds on the light distribution diagrams will be shown. The same blind types and tilt angles as those studied in chapter 7 will also be discussed here. The resulting light distribution histogram for the overcast sky scene is shown in Figure 9-15.

As seen from the results in Figure 9-15, the use of blinds increase the fraction of transmitted light in the upward directions. The reflective blind provides the highest fraction of transmitted light in the Up 0-30 direction (18.9%), and also the highest fraction of transmitted light in the Up 30-60 direction (40.1%). From this it can be concluded that the reflective blind here performs better than the white blind with respect to distributing the transmitted light towards the middle and deeper locations of the interiors.

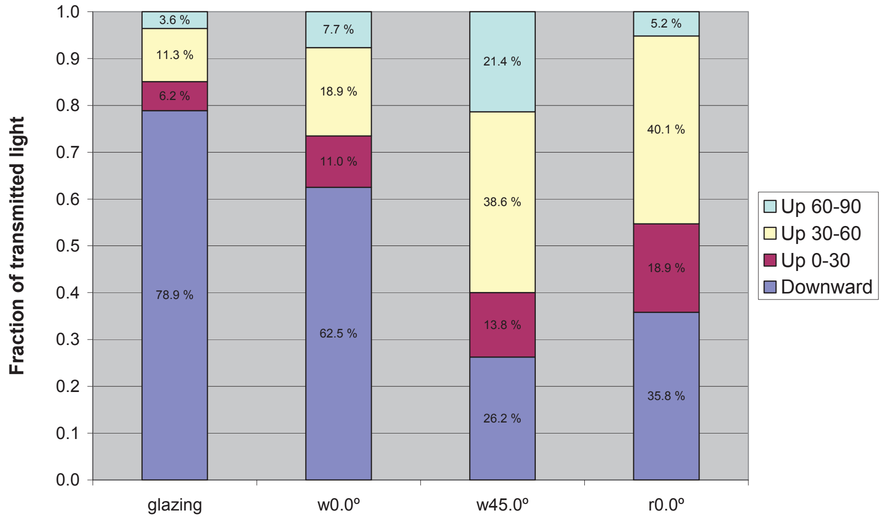


Figure 9-15 Light distribution histograms for various blind types and blind tilts under overcast sky conditions (S1).

9.3.3 High sun conditions

For all of the scenes considered, without blinds most of the transmitted light is directed downwards. As mentioned earlier, this light distribution can make the room appear gloomy. However, with blinds present, the fraction of transmitted light in the downward direction is significantly reduced (see the three following figures for scene 8, 9 and 10).

For the white blind, the fraction of downward transmitted light varies between 18.4% and 50.3%, while the fraction of transmitted light directed in the Up 0-30 direction lies between 12.1% and 19.7%.

For the reflective blind the fraction of downward transmitted light is 12.7% for scene 8 and 17.8% for scene 9. For scene 10 however, the fraction of downward transmitted light has increased abruptly to 71.5%! The fraction of transmitted light directed in the Up 0-30 direction is 85.0% for scene 8 and 79.4% for scene 9. However, for scene 10 it has suddenly dropped to 6.3%.

For scene 8 and 9 the results indicate that when the reflective blind is used in a sidelighted space, most of the light will be directed towards the middle locations of the room as well as the deeper interiors. This finding is supported by the results shown in section 7.6, and in particular by the results for ceiling illuminances given in Figure 7-4 and Figure 7-6.

For scene 9 it is interesting to observe that a large fraction of the transmitted light is redirected in the Up 0-30 direction (relatively close to the z-axis), and that this occurs even though the azimuth angle of the *incident* light is quite large (45º).

For scene 10 however, the results indicate that something has gone completely wrong regarding the redirection properties of the reflective blind. This result for scene 10 conforms to the results for light transmittance for this scene presented in Table 8-5 as well as the low floor illuminance levels given in Figure 7-8. The reason for this abrupt change in performance was explained in section 8.6.5: For this particular scene, due to the high projected solar elevation, most of the rays specularly reflected off one slat are directed towards the lower side of the overlying slat (see Figure 8-10). Clearly, this effect has a strong impact on both the *amount* and *distribution* of the transmitted light.

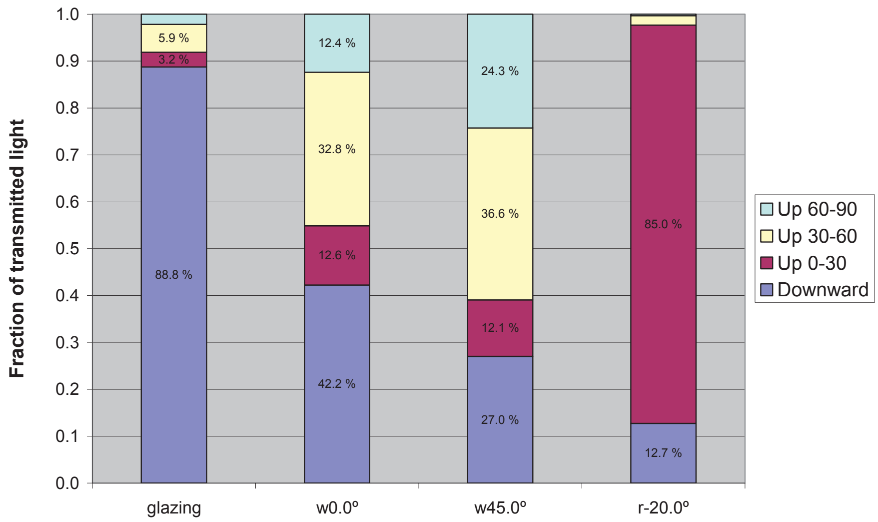


Figure 9-16 Light distribution histograms for various blind types and blind tilts under high sun conditions (S8).

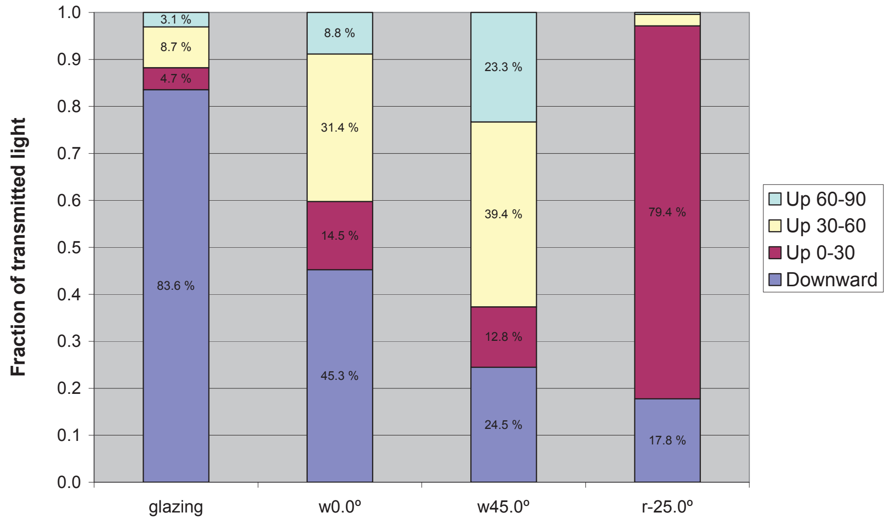


Figure 9-17 Light distribution histograms for various blind types and blind tilts under high sun conditions (S9).

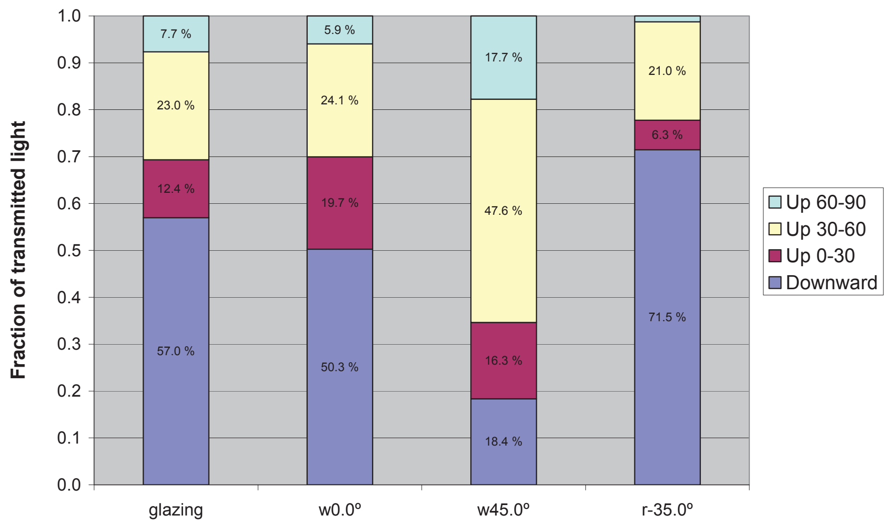


Figure 9-18 Light distribution histograms for various blind types and blind tilts under high sun conditions (S10).

9.3.4 Intermediate sun conditions

Without blinds, most of the transmitted light is directed downwards. As discussed above, this light distribution can make the room appear gloomy.

However, with blinds present, the distribution of downward directed light is significantly reduced. With the exception of the untilted white blind under scene 7, most of the transmitted light is now directed upwards.

For the white blind, the fraction of downward transmitted light varies between 24.0% and 55.0%, while the fraction of transmitted light directed in the Up 0-30 direction lies between 8.0% and 15.2%.

For the reflective blind most of the light is redirected in the Up 30-60 direction, and only a small fraction (4% or less) is directed in the Up 0-30 direction. This indicates that when this reflective blind configuration is used in a sidelighted space, most of the light will be directed towards the areas near the window facade and/or towards the middle locations of the space. This is supported by the results shown in section 7.7, and in particular by the results for ceiling illuminances given in Figure 7-10 and Figure 7-12.

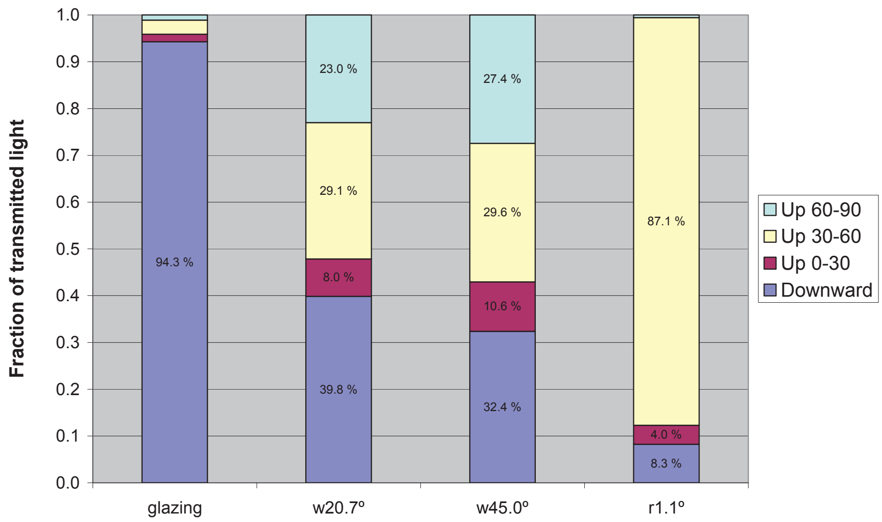


Figure 9-19 Light distribution histograms for various blind types and blind tilts under intermediate sun conditions (S5).

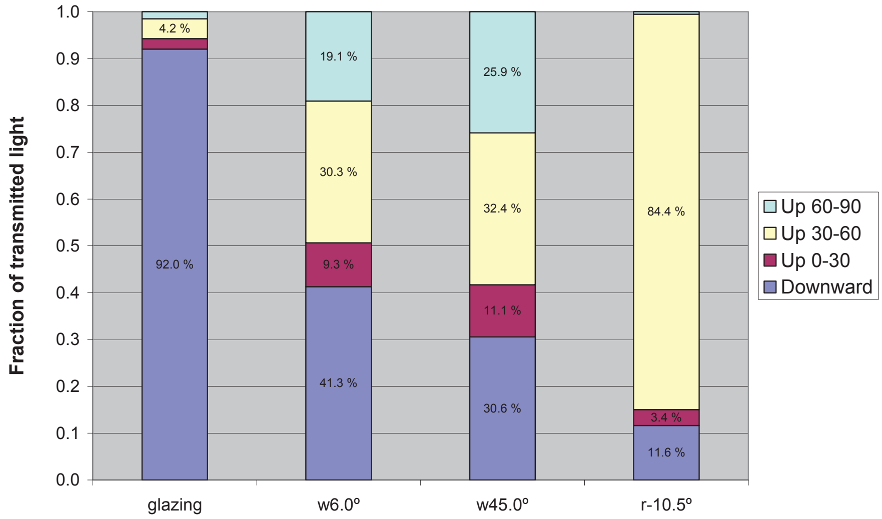


Figure 9-20 Light distribution histograms for various blind types and blind tilts under intermediate sun conditions (S6).

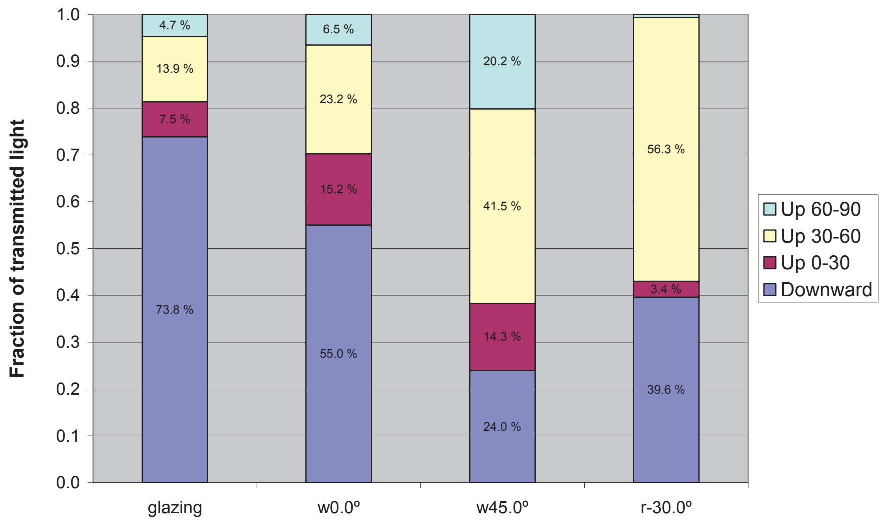


Figure 9-21 Light distribution histograms for various blind types and blind tilts under intermediate sun conditions (S7).

9.3.5 Low sun conditions

Also for low sun conditions, without blinds most of the transmitted light is directed downwards. Again however, with blinds present the fraction of downward directed light is significantly reduced.

For the white blind, the fraction of downward transmitted light varies between 34.1% and 50.8%, while the fraction of transmitted light directed in the Up 0-30 direction lies between 9.3% and 10.8%.

For the reflective blind the fraction of downward transmitted light varies between 17.6% and 22.4%, while the fraction of transmitted light directed in the Up 0-30 direction is 6.1% or less. From the histograms it is seen that most of the transmitted light is redirected in the Up 60-90 direction. This indicates that when the reflective blind is used in a sidelighted space, most of the light will be directed towards the areas near the window facade. This finding is supported by the results shown in section 7.8, and in particular by the results for ceiling illuminances given in Figure 7-16 and Figure 7-18.

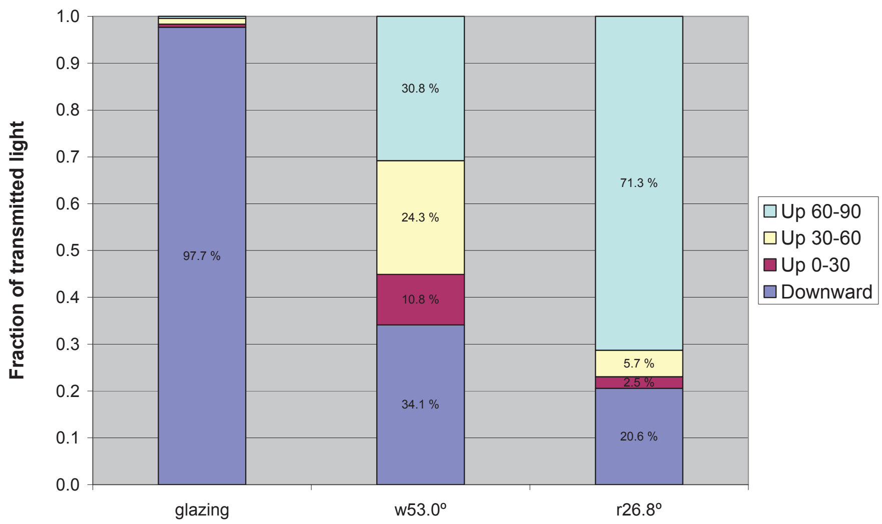


Figure 9-22 Light distribution histograms for various blind types and blind tilts under low sun conditions (S2).

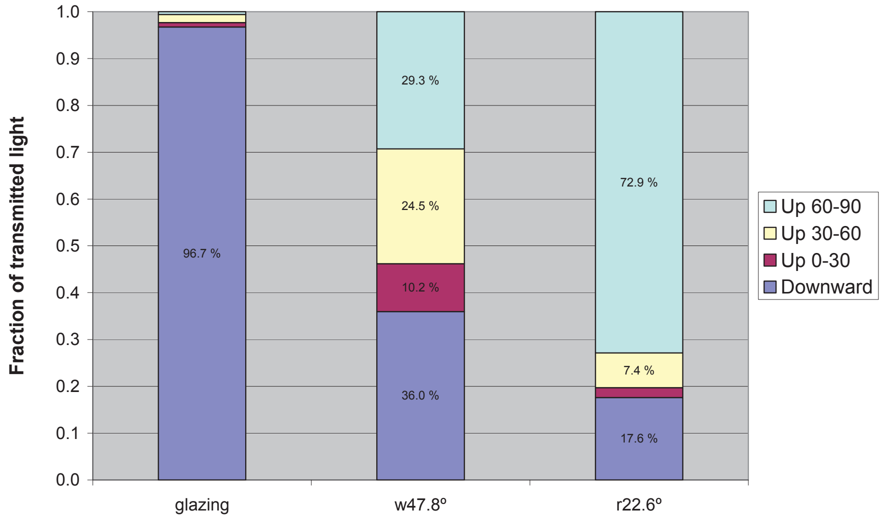


Figure 9-23 Light distribution histograms for various blind types and blind tilts under low sun conditions (S3).

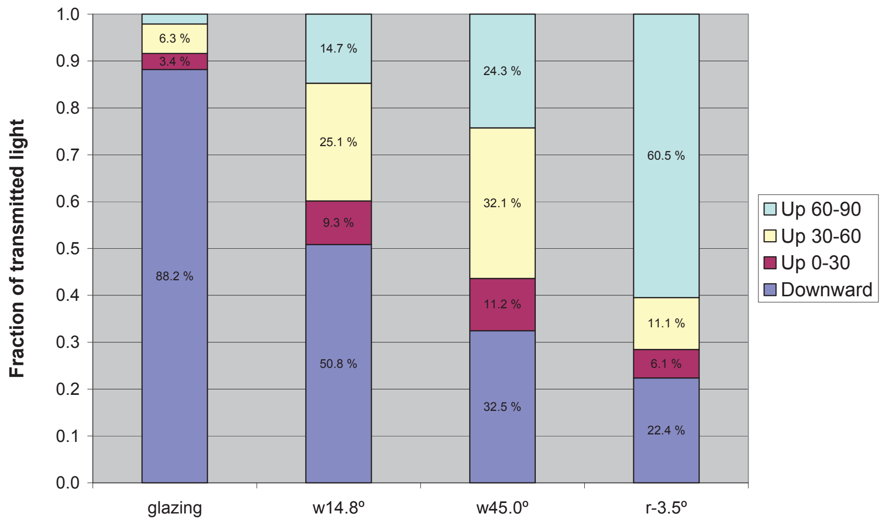


Figure 9-24 Light distribution histograms for various blind types and blind tilts under low sun conditions (S4).

9.3.6 Diffuse blind slats

In this section various distribution histograms for window openings with double glazing and blinds with diffuse slats are shown. The effects of blind tilting, spacing to width ratio and slat reflectance properties are investigated. Note that in this particular section a slat reflectance of 0.8 is used, as opposed to the "standard" reflectance of 0.7 used in previous sections.

The distribution of transmitted flux for untilted blinds in overcast sky conditions is shown in Figure 9-25. Compared to the situation without blinds, the fraction of transmitted flux in the upward directions has increased significantly, and the presence of the white blinds provides a more even distribution of the light. Also, the fraction of transmitted flux in the Up 0-30 region has increased. The results for different *S/W* indicate that the spacing to width ratio plays a minor role for the distribution of transmitted flux.

Results for a low sun scene (S2) are shown in Figure 9-26. Here the blinds are tilted for sunlight cut-off. Compared to the situation without blinds, the fraction of transmitted flux in the upward directions has again increased significantly. Also here, the fraction of transmitted flux in the Up 0-30 region has increased, but still only about 10% of the transmitted flux lies in the Up 0-30 region. The results for different *S/W* indicate that the spacing to width ratio here plays a minor role for the distribution of transmitted flux.

Results for an intermediate sun scene (S5) are shown in Figure 9-27, again with the blinds tilted for sunlight cut-off. The results follow the same pattern as before. Compared to the situation without blinds, the fraction of transmitted flux in the upward directions has again increased significantly. Also here, the fraction of transmitted flux in the Up 0-30 region has increased, but less than 10% of the transmitted flux lies in the Up 0-30 region. Also here the results for different *S/W* indicate that the spacing to width ratio here plays a small role for the distribution of transmitted flux.

Results for untilted blinds in a high sun scene (S8) are shown in Figure 9-28 and again, the fraction of transmitted flux in the upward directions has increased significantly compared to the situation without blinds. Also here, the fraction of transmitted flux in the Up 0-30 region has increased and lies between 11.7% and 14.9% for the blind with a slat reflectance of 0.8. The results for different *S/W* indicate that the spacing to width ratio again play a small role for the distribution of transmitted flux.

In chapter 8 it was shown that the reflectance values of the slats played a significant role for the *light transmittance*. Here however, the results provided in Figure 9-29 indicate that the reflectance values of diffuse slats do not play a large role for the *distribution* of transmitted flux.

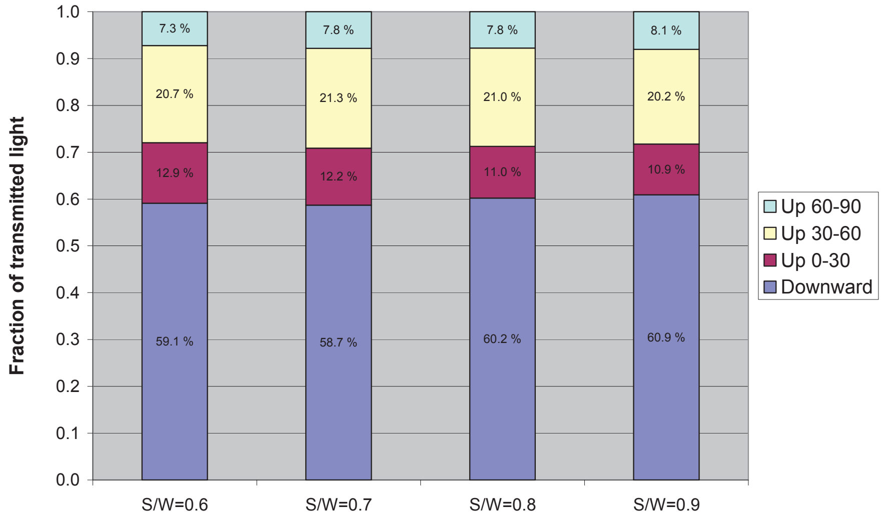


Figure 9-25 Distribution of light (flux) transmitted through a double glazing with untilted venetian blinds with diffuse white slats (ρ = 0.8) under overcast sky (S1).

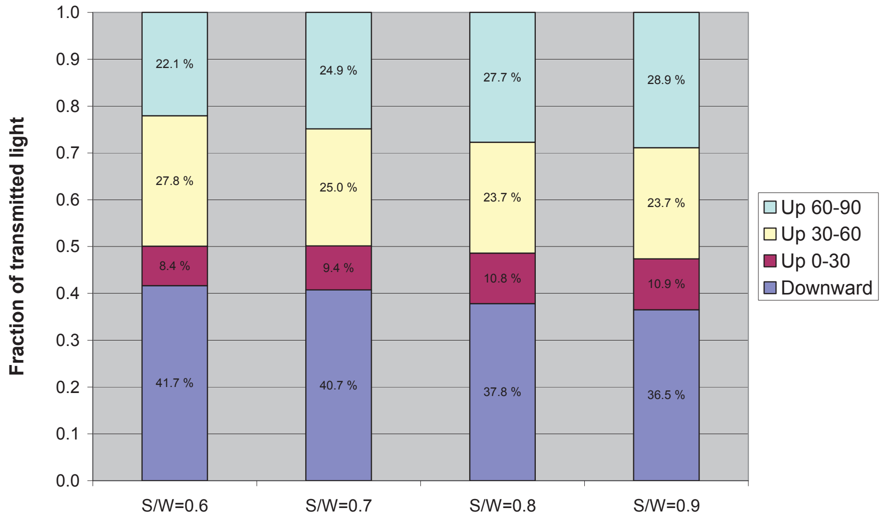


Figure 9-26 Distribution of transmitted flux through a double glazing with white venetian blinds (ρ = 0.8) tilted for sunlight cut-off under a low sun scene (S2).

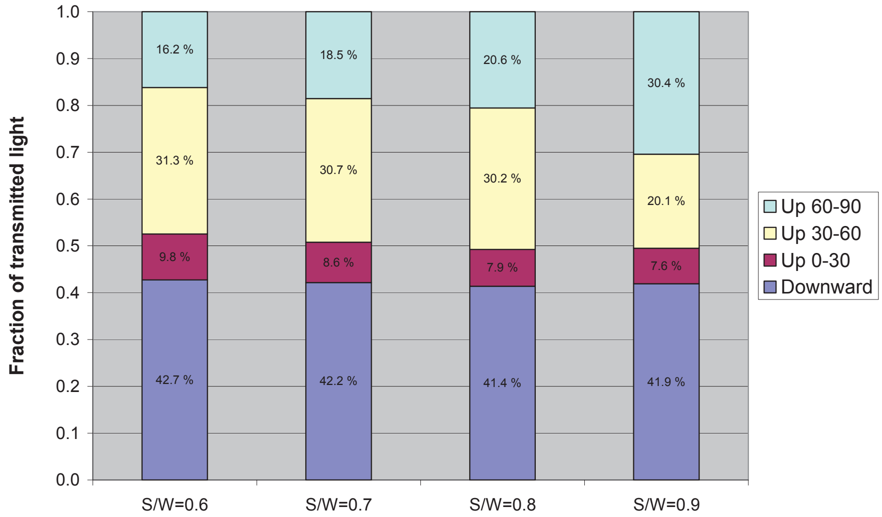


Figure 9-27 Distribution of transmitted flux through a double glazing with white venetian blinds (ρ = 0.8) tilted for sunlight cut-off under an intermediate sun scene (S5).

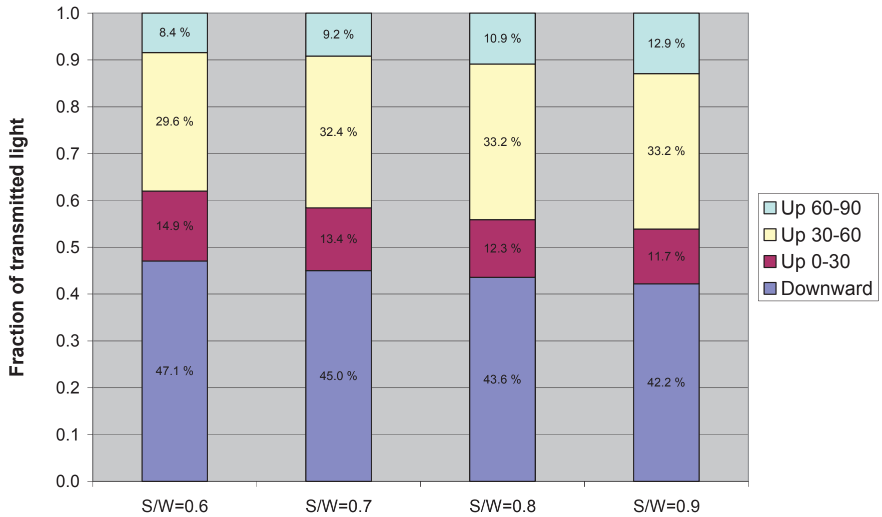


Figure 9-28 Distribution of transmitted flux through a double glazing with untilted white venetian blinds (ρ = 0.8) under a high sun scene (S8).

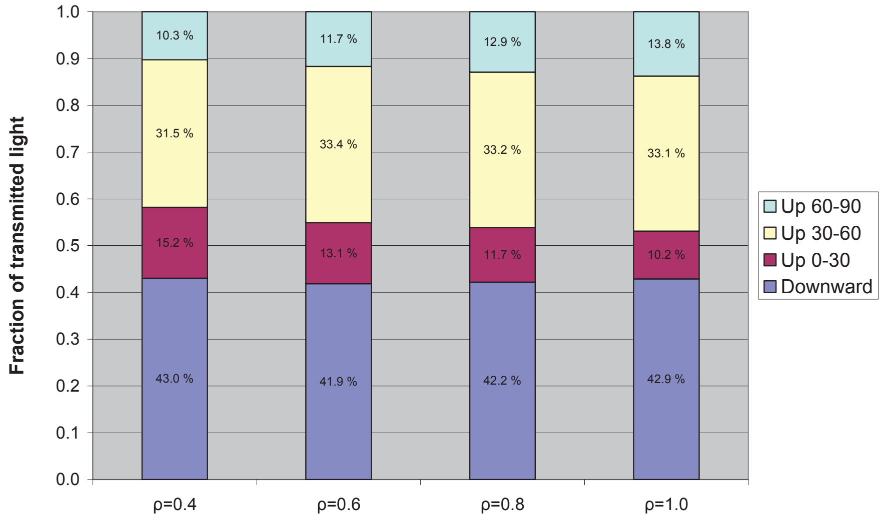


Figure 9-29 Distribution of transmitted flux through a double glazing with untilted white venetian blinds ($S/W = 0.9$) under a high sun scene (S8).

9.3.7 Effect of slat curvature

For the typical white blind with a slight slat curvature it is assumed that the curvature of the slats play a small role for the resulting distribution of the daylight within the interiors. The reason for this is that the white slat surface will diffuse the incident light and scatter it in all directions.

However, for the daylight redirecting reflective blind with specular slats the situation is very different. In this case the curvature of the slats could be very significant for the resulting distribution of the transmitted light.

With curved slats the direct sunlight reflected off the slats will not be collimated but rather spread out in the shape of a fan. This makes it more difficult to “control” the direction of the reflected sunlight by tilting the slats. For example, in order to avoid downward reflected sunlight, the slats now need to be more tilted compared to the situation with flat slats.

The fan-shaped redistribution of sunlight from a curved specular slat will affect the luminous intensity distribution of the transmitted light. This will result in a more even illuminance distribution of daylight on the ceiling (and side walls), since the redirected sunlight will be spread out over a larger area. For some of the daylight scenes discussed above, a slight curvature of the slats is assumed to influence the light distribution histograms. For example, the histograms for two of the high sun scenes (S8 and S9) are shown in Figure 9-16 and Figure 9-17. These histograms show that for flat blind slats, a very large fraction of the transmitted light lies in the Up 0-30 region. However, with curved slats it can be assumed that some of this light would be redirected in the Up 30-60 region instead.

It is also possible that for some of the daylight scenes the opposite effect will occur. For two of the intermediate sun scenes (S5 and S6) most of the daylight is redirected in the Up 30-60 region with flat blinds, as illustrated in Figure 9-19 and Figure 9-20. In these cases it is possible that slightly curved slats might redirect some of this light in the Up 0-30 region, and thus *increasing* the daylight levels in the deeper parts of the interiors.

9.4 Summary and conclusions

A main conclusion from the results presented in this chapter is that venetian blinds have the ability to significantly change the angular distribution of the transmitted flux, providing more light in the upward directions.

For diffuse (white) blinds neither the spacing to width ratio nor the slat reflectance seems to play a significant role for the distribution of transmitted flux. The fraction of transmitted flux in the upward directions is here typically from 40% to 60%. However, the fraction of transmitted flux in the Up 0-30 region is generally quite low, typically between 8% and 15%.

The reflective blind has the ability to redirect more light in the upward directions:

- For high sun conditions most of the light is transmitted in the Up 0-30 region. An exception is scene 10 where the result is changed dramatically and most light is directed downwards.

- For intermediate sun conditions most of the light is transmitted in the Up 30-60 region. Here scene 7 deviates somewhat from the other scenes due to the high projected solar elevation of this scene.

- For low sun conditions most of the light is transmitted in the Up 60-90 region. This is clearly not ideal for redirecting light deep into the building interiors.

10 Average window luminance

There are two kinds of light - the glow that illumines, and the glare that obscures.

James Thurber

10.1 Introduction

Windows are often associated with discomfort glare, especially under sunny conditions. According to Littlefair (1996), glare from windows usually arises when direct sunlight enters the room and shines into the eyes of occupants or reflects off visual tasks and surrounding surfaces. Alternatively, it may result from high window luminance caused by sunlight reflections off exterior surfaces or by a view of the sky.

A recent study by Shin et al. (2012) focused on discomfort glare assessments from windows. One of the conclusions was that the mean luminance of the window had a relatively large influence on the subjective assessment of discomfort glare. In addition, the experiments carried out indicated that both the types of view as well as the distance of the view object are critical factors for the subjective evaluation of discomfort glare.

High window luminances can result both from the luminance of the sky or scenery behind the window or from light reflected from the surfaces of the fenestration system. For this reason, it is of interest to study the average window luminances that are obtained for various daylight scenes and for various venetian blind solutions (including slat reflectance and tilt angle). Window luminance is therefore the subject of this chapter.

10.2 Acceptable luminance levels

Acceptable window luminance levels for windows were discussed in section 2.3.2. Some studies suggests that upper limits for window luminance lies around 2500 cd/m^2 (Fisekis 2003) while other studies suggests higher levels between 4000 cd/m^2 and 6000 cd/m^2 (Platzer 2003).

It is important to note that the window luminance levels described in the literature are mainly derived for tests with view windows. In the work of Luckiesh and Guth (1949) and, more recently, the work of Kim and Kim (2010) it was clearly demonstrated that the glare sensation drops significantly when the glare source is located above the line of sight. For this reason it is reasonable to assume that higher luminance values can be acceptable for elevated daylight openings than for view windows. Guidelines for acceptable luminance levels in elevated daylight openings have so far not been established.

10.3 Luminance map capabilities in TracePro

Unfortunately, TracePro is not the most suitable tool for obtaining luminance maps that quantify the window luminance. It is therefore not straightforward to use TracePro for a detailed assessment of glare.

As described earlier, the software TracePro is based on a forward ray tracing approach. This approach has several advantages in the study of the optical performance of a system, but also some drawbacks. One drawback of forward ray tracing compared to backward ray tracing is that it is not suitable with respect to creating a photorealistic image of a lit scene. Backward ray tracing can allow the user to determine a point in space and trace a large number of rays backwards onto the scene from this exact position, generating an image of the scene. This is not possible by a forward ray tracing approach.

In TracePro, this deficit has been addressed by introducing some backward ray tracing capabilities that can be applied for certain situations where forward ray tracing is not suitable. One of the possibilities that this opens in TracePro is the possibility to generate luminance maps of a lit scene. Unfortunately, luminance maps can not be created for all types of “light sources” applied in TracePro. At least for the current version of TracePro, luminance maps can not be created for models that are “illuminated” by ray files of the type constructed to represent the 10 daylight scenes under consideration. This shortcoming makes it somewhat problematic to use TracePro to assess glare from daylight.

Even so; information about the *average* window luminance when the window is observed from a long distance can be obtained by utilising the data from the luminous intensity plots discussed in chapter 9. A calculation method for average window luminance is discussed in the following sections.

10.4 Forward ray tracing approach for calculation of average window luminance

As shown in chapter 9, forward ray tracing can provide detailed information about the luminous intensity distribution of the light entering through a fenestration system. For each and every direction, the average luminance of the window opening, as seen from a distance, can be calculated by dividing the luminous intensity value by the projected area of the window opening in that direction. By this approach it is possible to utilise the luminous intensity data obtained from TracePro to identify directions from which an observer might experience a particularly high window luminance. It should be noted that the luminous intensity plots obtained from a TracePro simulation does not distinguish between light from the sky and light reflected off the surfaces of the daylighting system (e.g. blind slats). This means that the window area will typically contain regions with luminance values that are both higher and lower than the calculated average value.

This approach for calculating the average window luminance can be compared to the "average luminance method" used in glare assessment for luminaires, as described in CIE technical report 121 (CIE 1996). Here it is described that; *"to obtain the average luminance of a luminaire, the intensity in the relevant directions should be measured and divided by the orthogonally projected area of all those parts of the luminaire that emit light in that direction"*.

10.4.1 Validation of average window luminance

TracePro simulations without any glazing or daylighting components present in the window opening can be used to validate the ray tracing approach for calculation of average window luminance. In this case the average window luminance in a given direction should be equal to the sky luminance in that same direction.

For validation purposes the direction towards a sky element given by an elevation angle (γ) of 10º and an azimuth angle relative to the window normal ($\Delta\alpha$) of 0º (see Figure 4-1.) is used. This corresponds to the direction specified by a polar angle of 10º and an azimuth angle of 180º as given in the candela plots.

The chosen direction seems to be a quite relevant direction to consider; for example when an elevated window opening (located above eye height) is viewed from a long distance. Also, more upward directions will typically be farther from the line of sight, and will therefore typically be less critical with respect discomfort glare.

The luminous intensity distribution plots for all of the 10 daylight scenes under consideration are given in section 9.2.2. From these plots, the luminous intensity (I) in the direction of interest can be obtained, and the average window luminance (L) in the direction of interest can be calculated from the following equation:

$$L_{win\_avg\_10^o} = \frac{I_{10^o,180^o}}{\mathrm{A}_{win} \cdot \cos 10^o} \tag{10.1}$$

Here, the denominator represents the orthogonally projected window area in the direction of interest.

The sky luminance in the direction of interest can be found directly from equations 5.3 (overcast sky) and 5.5 (clear skies). The mathematically obtained values can be used for validation of the results from the ray tracing approach.

A comparison of the (average) window luminance values obtained by the ray tracing approach (with TracePro) and by mathematical calculations is given in Table 10-1. The results show that the TracePro simulations constantly give a value that is too low; by approximately 8%. This systematic error is believed to be caused by the TracePro ray files that represent the 10 daylight scenes. All the 10 ray files are constructed based on an identical random number generation process. The results presented in Table 10-1 seem to indicate that 30.000 rays are not enough to provide high accuracy for luminance calculations. However, the accuracy is considered to be acceptable when the average window luminance is used only as a means to compare different blind types and blind tilts.

Table 10-1 Average window luminance values for different daylight scenes obtained by a forward ray tracing approach (TracePro) and by mathematical calculations.

Scene	Window luminance (in the direction given by γ =10º, $\Delta\alpha$ = 0º)		
	TracePro [cd/m^2]	Mathematical [cd/m^2]	Difference [%]
1	1834	1986	7.6%
2	11041	11948	7.6%
3	3958	4270	7.3%
4	2139	2324	8.0%
5	15762	17109	7.9%
6	7795	8434	7.6%
7	4581	4970	7.8%
8	10111	11006	8.1%
9	7300	7924	7.9%
10	5214	5667	8.0%

10.5 Average window luminance for selected blind configurations

In the following sections average window luminances for selected blind configurations are provided. All luminances are calculated in the direction discussed above, that is, with $\gamma = 10^o$ and $\Delta\alpha = 0^o$. As noted above, this particular direction is chosen as it seems to be a quite relevant direction to consider; for example when an elevated window opening (located above eye height) is viewed from a long distance.

10.5.1 Overcast sky

The average window luminance for selected blind configurations under overcast sky conditions (S1) is given in Table 10-2. As expected, the highest average window luminance is obtained when no blinds are present in the window opening (NB). For the untilted blinds, the reflective blind provides a slightly lower average window luminance than the white blind (991 cd/m^2 compared to 1265 cd/m^2). The configuration that gives the lowest potential glare problems is the white blind tilted at 45º, providing an average window luminance of 305 cd/m^2.

Table 10-2 Average window luminance for selected systems under overcast sky.

Scene	Blind configuration	Window luminance [cd/m^2]
1	NB	1542
1	w0º	1265
1	w45º	305
1	r0º	991

10.5.2 High sun conditions

In this section the average window luminance of the selected systems under high sun conditions is discussed. The average window luminances obtained for the high sun scenes are given in Table 10-3.

Again, as expected, for all the three scenes the configuration without any blinds gives the highest average window luminance.

A significant reduction in the average window luminance is obtained for the white blind tilted with a slat angle of 45º. For this blind configuration the average window luminance has been reduced by 57% (S8) to 77% (S10) compared to the window luminance of the glazed window without blinds.

Both for the untilted white blind and for the reflective blind (tilted for daylight redirection) the average window luminance is only moderately reduced compared to the situation without blinds.

Table 10-3 Average window luminance for selected systems under high sun.

Scene	Blind configuration	Window luminance [cd/m^2]
8	NB	8504
8	w0º	7798
8	w45º	3658
8	r-20º	8246
9	NB	6132
9	w0º	5790
9	w45º	2305
9	r-25º	5804
10	NB	4378
10	w0º	3624
10	w45º	1016
10	r-35º	3072

10.5.3 Intermediate sun conditions

In this section the average window luminance of the selected systems under intermediate sun conditions is discussed. The average window luminances obtained for the intermediate sun scenes are given in Table 10-4.

The results follow the same pattern as for high sun.

Again, as expected, for all the three scenes the configuration without any blinds gives the highest average window luminance.

A notable reduction in the average window luminance is obtained for the white blind tilted with a slat angle of 45º. For this blind configuration the average window luminance is reduced by 61% (S5) to 76% (S7) compared to the window luminance of the glazed window without blinds.

Again, both for the untilted white blind and for the reflective blind (tilted for daylight redirection) the average window luminance is generally only moderately reduced compared to the situation without blinds.

Table 10-4 Average window luminance for selected systems under intermediate sun.

Scene	Blind configuration	Window luminance [cd/m²]
5	NB	13247
5	w20.7°	9097
5	w45°	5156
5	r1.1°	10241
6	NB	6554
6	w6.0°	5913
6	w45°	2806
6	r-10.5°	6298
7	NB	3855
7	w0°	3296
7	w45°	942
7	r-30°	2869

10.5.4 Low sun conditions

In this section the average window luminance of the selected systems under low sun conditions is discussed. The average window luminances obtained for the low sun scenes are given in Table 10-5.

Again, as expected, for all the three low sun scenes the configuration without any blinds gives the highest average window luminance.

For scene 2, both the white blind and the reflective blind reduce the average window luminance significantly; from 9285 cd/m^2 to 2211 cd/m^2 and 2141 cd/m^2 respectively. The reason for this is the relatively large slat tilting needed to provide sunlight cut-off for the low sun.

The same tendency is seen for scene 3. Here, the average window luminance is reduced from 3327 cd/m^2 (without blinds) to 1644 cd/m^2 with the white blind and to 1309 cd/m^2 with the reflective blind.

For scene 4, due to the high *projected* solar elevation, the white blind and the reflective blind are less tilted (nearly untilted). For this reason the reduction in average window luminance is much less than for scenes 2 and 3. However, the absolute level of the average window luminance in the direction under consideration is relatively low, due to the low sky luminance obtained for this particular scene.

Table 10-5 Average window luminance for selected systems under low sun.

Scene	Blind configuration	Window luminance [cd/m^2]
2	NB	9285
2	w53.0º	2211
2	r26.8º	2141
3	NB	3327
3	w47.8º	1644
3	r22.6º	1309
4	NB	1799
4	w14.8º	1152
4	w45º	510
4	r-3.5º	1430

10.6 Summary and conclusions

In this chapter it has been shown that TracePro can be used to obtain values for the average window luminance for different blind types and blind tilts under different daylight scenes. Both the luminance of the blind slats and the luminance of the sky (as seen between the slats) contribute to the average window luminance.

The results presented in Table 10-1 show that the sky luminance in the direction given by $\gamma = 10º$ and $\Delta\alpha = 0º$ varies significantly for the 10 daylight scenes under consideration. The three scenes with the highest sky luminance in this direction are scenes 5, 2 and 8, all of which give luminance values above 10 000 cd/m^2.

These high luminances might very well not be tolerable for the building occupant, even when they occur only at elevated locations (in window openings lying above eye height).

The results with blinds in the window opening show that the average window luminances depends largely on the type of blind and the mode of blind operation, as defined in section 7.3.

The results show that the white blind generally reduces the average window luminance significantly when it is tilted in the semi-closed position ($\beta = 45º$). For the 9 sunlight scenes the luminance values lie between 510 cd/m^2 (for scene 4) and 5156 cd/m^2 (for scene 5).

However, when the white blind is in the open blind position, so as to admit more daylight or to provide better conditions for viewing in the horizontal direction, the average window luminances are only moderately reduced compared to the situation without blinds (NB). The average window luminance values obtained for the open white blind lie between 3072 cd/m^2 and 8246 cd/m^2 for the high sun scene, and between 3072 cd/m^2 and 9097 cd/m^2 for the intermediate sun scene. For the low sun scene the average window luminance lies below 2211 cd/m^2.

For the reflective blind (tilted in the open position for sunlight redirection) the results are comparable to those obtained for the open white blind. The average window luminance values obtained for the reflective blind lie between 3624 cd/m^2 and 7798 cd/m^2 for the high sun scene, and between 2869 cd/m^2 and 10 241 cd/m^2 for the intermediate sun scene. For the low sun scene the average window luminance lies below 2141 cd/m^2.

The average window luminance values obtained with the blinds (white or reflective) in the open position might be considered unacceptable by a building occupant. For some daylight scenes this might even apply with a white blind tilted at 45º. For several of the daylight scenes under consideration the reflective blind (tilted in the open position for sunlight redirection) provides the highest values for average window luminance. For this reason it is of interest to consider the performance of the reflective blind tilted at other (more closed) tilt angles. Some results for average window luminance from semi-closed positions of the reflective blinds are presented and discussed in chapter 13.

11 Total solar energy transmittance

When you can't make them see the light, make them feel the heat.

Ronald Reagan

11.1 Introduction

In previous chapters the transmittance and distribution of visible daylight entering through a daylighting system was studied. Clearly, the performance of a daylighting system with respect to visual light is of major importance.

However, for building energy calculations the total solar energy transmittance through fenestration systems also play a significant role. It can be argued that overheating protection is a major reason for applying solar shading components in the window openings and it is therefore of interest to consider the performance of venetian blind systems also with respect to solar energy transmittance.

In this chapter the total solar energy transmittance of interior venetian blinds is studied. A new approach for the calculation of total solar energy transmittance is proposed. With a few simplifying assumptions, this enables the use of TracePro to calculate solar energy transmittance. This is convenient in that the computer models of different blind configurations that are constructed in TracePro can be used directly to provide useful information about the heat protecting properties of the different blind types and their mode of operation (blind tilt).

Since the new approach is based on some simplifying assumptions, the main aim has not been to produce very accurate results, but rather to produce results with an accuracy that is satisfactory for comparing different blind systems, or to indicate the effect of a change in parameters such as slat reflectance, blind tilting or spacing to width ratio.

11.2 Basic principles

As illustrated in Figure 11-1, the total solar energy transmittance (g-value) consists of two parts, the solar transmittance (τ_{sol}) and the secondary internal heat transfer factor (q_i).

$$g = \tau_{sol} + q_i \tag{11.1}$$

The g-value of a fenestration system can be measured or calculated. Exact calculation requires a detailed knowledge of the fenestration systems optical and thermal properties, including the variation with the angle of incidence of the solar radiation. In addition, for adjustable fenestration systems such as venetian blinds, the g-value could depend strongly on the mode of operation (blind tilt) of the system.

Therefore, simplifying assumptions are often made in the calculation of g-value. For example, for calculation of g-value for venetian blinds it is often assumed that the sunlight is incident from an elevation angle of 45º and an azimuth difference angle of 0º, and also, that the blinds are tilted at 45º (CEN 2003; CEN 2003).

Since detailed measurements of complex fenestration systems are laborious, there has been a need for better methods to model the total solar energy performance. Efforts that have been made to address these needs includes the development of a new model for double glazing units incorporating venetian blinds (Breitenbach, Lart et al. 2001), as well as a new approach based on a forward ray tracing methodology (Kuhn, Bühler et al. 2001). As noted by Kuhn, a realistic and reliable evaluation of the overheating protection requires that the angular distribution of the incident radiation is taken into account, and this can be achieved with the recommended ray tracing methodology.

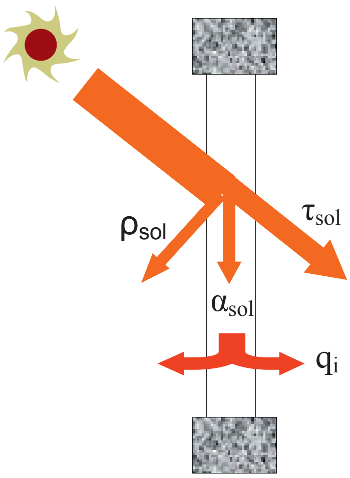


Figure 11-1 Illustration of solar energy transmittance through a fenestration system.

11.3 Ray tracing approach for calculation of solar energy transmittance

As discussed above, the g-value consists of two parts; the solar transmittance (τ_{sol}) and the secondary internal heat transfer factor (q_i).

Since TracePro does not account for thermal heat transfer, the exact g-value can not be easily obtained by a TracePro simulation. However, under certain conditions it is possible to provide an estimated g-value based on TracePro simulations.

The approach outlined here is similar to that discussed by Kuhn (2001) but includes some simplifying assumptions about the properties of the fenestration system.

The first simplifying assumption is that there is no absorption of solar energy within the double glazing unit. This is correct when the materials used in the glazing are non-absorbing for radiation in the solar spectral region. As long as materials with little solar absorptions are used, the error from this assumption is relatively small.

The second assumption is that all heat absorbed on the slats of the interior blinds remain within the interiors, and contribute to the interior heat gains. This is a reasonable assumption since glass generally has a low transmittance for thermal radiation.

With these assumptions the daylight gains can be found from optical ray tracing simulations by considering the fraction of light that is either transmitted through the blind system or absorbed on the slat surfaces (located on the interior side of the double glazing unit).

For calculation of total solar energy transmittance, the optical properties entered into the TracePro model of the blind system should represent the whole spectral energy region of daylight, and not only the visible region. For this reason the total solar reflectance (ρ_{sol}) should be used to specify the slat surfaces instead of the visible reflectance (ρ_{vis}).

Furthermore, the angular distribution of incident radiation should represent the angular distribution of *solar energy* (in radiometric units) and not the distribution of *visible light* (in photometric units). Therefore, ideally, the daylight distributions described in chapter 5 should be modified to represent the angular energy distribution from daylight.

Such a modification of the daylight distributions has not been carried out and will not be presented here. However, it is argued that the resulting error from using the photometric distribution of daylight is acceptable. Anyhow, compared to the customary approach of taking only direct sunlight into account, using the daylight distributions of incident light as proposed here must be considered a significant step forward. To support this argument it is noted that the luminous efficacy of direct sunlight and global radiation is comparable; 93 lm/W and 108 lm/W respectively according to Löfberg (1976). This means that the angular distribution of visible daylight is similar to the distribution of energy from the sun and sky.

The main positive attribute of the proposed approach is that it takes into consideration both the sky type and the optical properties of the fenestration system, including the mode of operation (blind tilt) of venetian blinds as well as the solar reflectance properties of the slat surfaces.

Finally, it is noted that the proposed approach will be used primarily to compare the performance of similar venetian blind systems, and not to quantify heat gains. This reduces the need for absolute accuracy.

With the proposed method, the estimated g-value (g) is calculated from a TracePro simulation by applying the following equation:

$$g = \tau_{sol} + a_{slats} = 1 - \rho_{win} \tag{11.2}$$

Here τ_{sol} is the solar transmittance of the fenestration system (including the effect of the window panes), a_{slats} is the absorptance of solar radiation on the slats of the interior blinds and ρ_{win} describes the fraction of incident flux that is directed back from the window opening.

To summarise; following from a TracePro simulation it is straightforward to keep track of the fraction of incoming flux that is directed back from the window surface (ρ_{win}). This can be used to provide an estimate for the g-value of a fenestration system with interior blinds under a given daylight scene.

11.4 Validation of ray tracing approach

As a first validation of the ray tracing approach, results from this method has been compared to results obtained by the traditional method described in CEN (2003). This means that a new ray source have been constructed in TracePro representing direct sunlight incident from a solar elevation of 45º and an azimuth difference of zero ($\Delta\alpha$ = 0º). Results from calculation of total solar energy transmittance are provided in Figure 11-2.

The results based on TracePro simulations are obtained for a white blind with spacing to width ratio of 0.8, and a blind tilting (β) of 45º. Four different slat reflectance values have been simulated; from 0.0 to 1.0 (diffuse reflectance). The results show the combined effect of the blind and the double glazing unit.

The results based on the simplified method given by the CEN (2003) standard are taken from a blind manufacturers catalogue (HD 2007). Results for slats with solar reflectance from 0.05 to 0.81 are provided. The results again show the combined effect of blinds and double glazing unit.

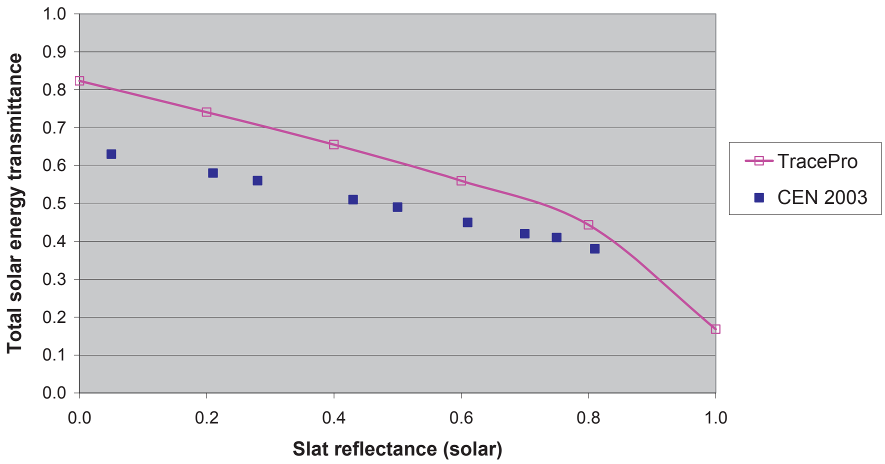


Figure 11-2 Total solar energy transmittance for a double glazing unit with interior blinds tilted at 45º.

The results show that the TracePro approach gives significantly higher values. The main reason for this lies in differences of the double glazing unit. In the TracePro model, the window panes are assumed to be non-absorbing; resulting in a double glazing unit with a g-value of 0.82. The calculations according to the CEN standard are based on a double window glazing with a g-value of 0.70.

For the TracePro simulations, as the slat reflectance approaches zero, the g-value of the fenestration system is expected to approach that of the double glazing unit (without blinds), since for this approach all transmitted energy is assumed to stay within the interiors. If the g-value of the double glazing unit itself had been 0.70 instead of 0.82 for the TracePro simulations; the obtained results would be much closer to those based on the CEN standard. It should also be mentioned that the CEN standard itself only describes a simplified method, and the results from this method should not considered accurate.

For the TracePro simulations, another source of error lies in the threshold values used to terminate a ray trace. In order to limit the number of rays accounted for in a TracePro simulation, rays are terminated when the flux reaches a certain threshold value as compared to the starting flux of the original incident ray. Unless this threshold value is set to a very low number (increasing the simulation time), the flux of these terminated rays may add up to a significant size. In the calculation of total solar transmittance according to equation 11.2, the flux of terminated rays will be regarded as absorbed flux, and will reduce the value of the flux that is directed (reflected or transmitted) back from the window opening (ρ_{win}). This will result in slightly overestimated values for total solar energy transmittance.

The effect of this error source can be seen from Figure 11-3. The results are obtained for blinds that are completely closed. A flux threshold of 0.01 was used for ray termination, meaning that a ray is terminated if the flux associated with that ray drops to less than 1% of the starting flux. With blinds fully closed it would be expected that the calculated g-value drops to zero when the slat reflectance is 1.0. The reason for this is that no light is transmitted through the fully closed blinds and no light is absorbed, either at the slat surfaces or in the window panes. However, the results indicate a total solar energy transmittance of approximately 0.04 when the blinds are fully closed. And the main reason for this is found to be the contribution of flux from terminated rays.

The results above indicate that the flux threshold introduces an absolute error of up to approximately 0.04 in the calculation of g-values. In order to obtain more accurate results the flux contribution from terminated rays should be reduced or eliminated. It is possible to reduce the flux from terminated rays by reducing the threshold flux for ray termination, but this will increase the processing time for each simulation. It is also possible to locate the flux from terminated rays from a TracePro flux report, and to use this information to correct the results. This last solution is quite laborious (at least when it is done manually). The results presented in this chapter are therefore not corrected with respect to flux from terminated rays.

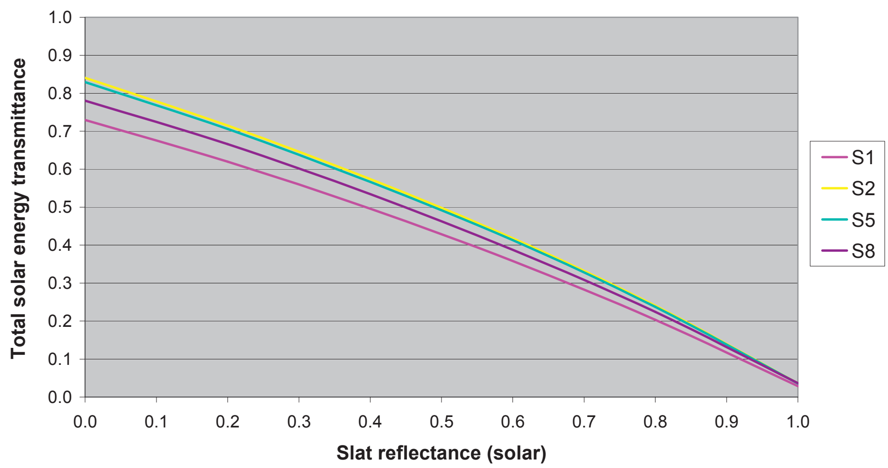


Figure 11-3 Total solar energy transmittance for blinds that are fully closed under different daylight scenes.

11.5 Diffuse blind slats

In this section the performance of interior venetian blinds with a diffuse slat surface is considered.

In calculations of g-values for venetian blinds (combined with glazing) it is customary to set the blind tilt to an angle of 45º. As discussed above, it is also often assumed that all light is incident from an elevation angle of 45º. By this assumption, the diffuse skylight and ground reflected light is not taken into account.

In Figure 11-4 the g-values calculated by the ray tracing approach for blinds tilted 45º is shown. Incident light includes both direct sunlight, diffuse skylight and ground reflected light as defined by scene 5 (intermediate sun). The results show that the g-value is strongly depending on the reflectance of the blind slats. Blinds with a low slat reflectance will absorb most of the light transmitted through the glazing, and the g-values approaches those obtained for the glazing without any blinds present. For perfectly absorbing slats the solar energy transmittance is 83%; the same as the transmittance for a double glazing for scene 5 as given in Table 8-1. For high reflectance values, the blind slats absorb only a small fraction of the light. In this situation, the main component to the total solar energy transmittance is radiation transmitted between the slats of the venetian blind system and absorbed within the interiors.

It is of interest to quantify the g-values provided by blinds that are not tilted at 45º.

In Figure 11-5 total solar energy transmittance (g-value) is shown for untilted blinds under overcast sky conditions. As expected, the g-values can be reduced by increasing the slat reflectance. The spacing to width ratio (*S/W*) has only a small impact on the g-value.

In Figure 11-6 the g-values obtained for blinds tilted for sunlight cut-off (open blinds) for low sun (S2) is shown. The results show that the blinds with larger *S/W* give a slightly lower g-value. The reason for this is that more blind tilt is needed to obtain sunlight cut-off for larger *S/W* and this reduces the g-values. The same conclusion can be seen for intermediate sun (S5), as shown in Figure 11-7.

Results for high sun (S8) are shown in Figure 11-8. Here the blinds are kept untilted. In this situation a larger S/W gives a higher g-value, but the relative difference is quite small.

The lowest solar energy transmittance is provided when the blinds are fully closed. For perfectly closed blinds, the spacing to width ratio is no longer relevant. Results for this situation have already been discussed and are provided in Figure 11-3.

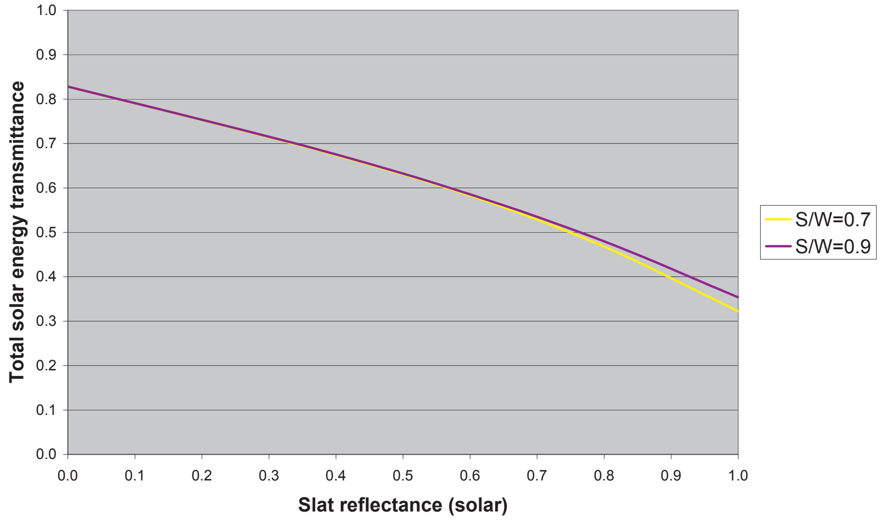


Figure 11-4 Total solar energy transmittance for blinds tilted 45 degrees. Incident light includes both direct sunlight, diffuse skylight and ground reflected light as defined by scene 5 (intermediate sun).

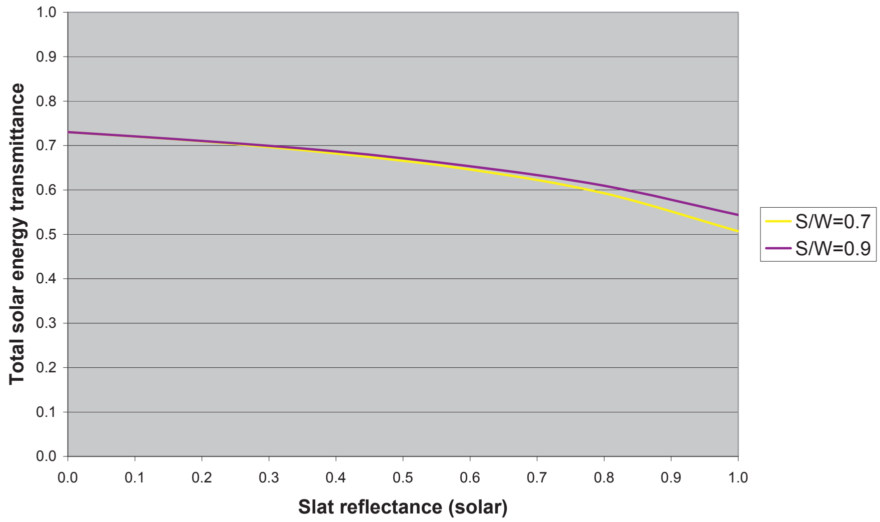


Figure 11-5 Total solar energy transmittance for blinds untilted blinds in overcast sky conditions (S1).

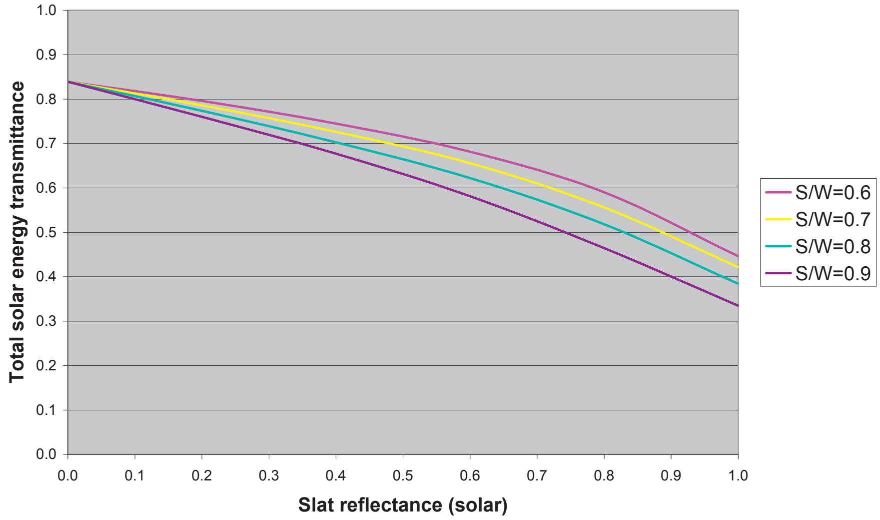


Figure 11-6 Total solar energy transmittance for blinds tilted for sunlight cut-off. Incident light includes both direct sunlight, diffuse skylight and ground reflected light as defined by scene 2 (low sun).

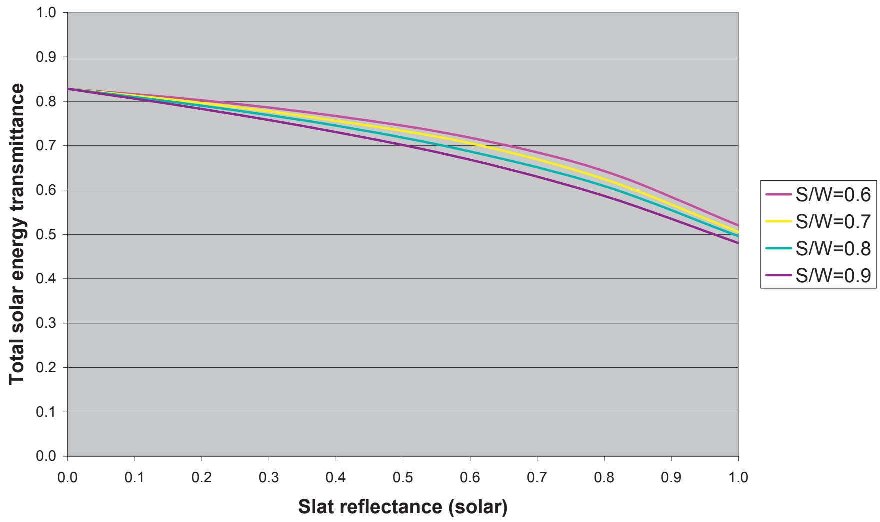


Figure 11-7 Total solar energy transmittance for blinds tilted for sunlight cut-off. Incident light includes both direct sunlight, diffuse skylight and ground reflected light as defined by scene 5 (intermediate sun).

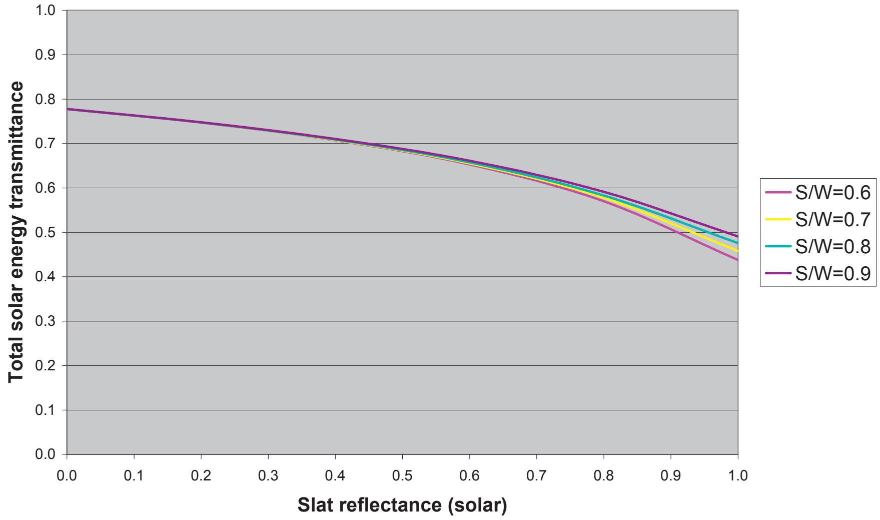


Figure 11-8 Total solar energy transmittance for untilted blinds. Incident light includes both direct sunlight, diffuse skylight and ground reflected light as defined by scene 8 (high sun).

11.6 Summary and conclusions

The results presented in this chapter indicate that forward ray tracing can be used to provide an estimate for total solar energy transmittance for a double glazing unit in combination with interior venetian blinds. As expected, the results show that the g-value depends strongly on the solar reflectance of the blind slats as well as of the tilt angle.

It is commonplace to specify the g-value for blinds tilted 45º. For this tilt angle, the results show that the g-value also varies significantly with the slat reflectance.

More importantly, the results show that the mode of operation (blind tilt) is of importance. For scene 5 (intermediate sun) the results show that the total solar energy transmittance is lower for semi-closed blinds ($\beta = 45º$) than for open blinds (tilted for sunlight cut-off).

The results also seem to indicate that the spacing to width ratio (*S/W*) here is of less importance, at least for blinds with diffuse slats.

12 Evaluation method for daylight redirection systems

Create your own method. Don't depend slavishly on mine. Make up something that will work for you! But keep breaking traditions, I beg you.

Konstantin Stanislavski

12.1 Introduction

In previous chapters it has been shown that the transmittance and luminous intensity distributions of fenestration systems can vary significantly. For venetian blind type systems, the slat reflectance and slat tilting often plays a major role, and sometimes also the spacing to width ratio of the blind. In addition, the transmittance and luminous intensity distribution also varies strongly with the daylight scene.

In this chapter a new method for evaluation of daylight redirection systems is proposed and described. The new method can be used to quantify several characteristics that are considered important for fenestration systems in general and daylight redirection systems in particular. The method is intended to be used for systems that are located in elevated window openings, above eye height of the building occupant. The method is primarily developed for slat type systems. However, with some slight modifications the method can also be applied to other types of daylight redirection systems, such as for example prismatic elements or laser cut panels.

The main goal of the method is to provide a tool that can be used to indicate the performance of a particular system with respect to all important characteristics that are determined by the optical properties of the daylighting system under a particular daylight scene. This means that characteristics that are influenced by factors such as slat reflectance, slat tilting and blind geometry will be considered.

It has been a goal to present a methodology that, as far as possible, can predict the performance of the daylight redirection system itself, and not the ability of a particular space to utilise daylight form a daylighting system.

The proposed method can be useful for comparing different daylight redirection systems and illustrating how the performance of a system changes with different system configurations (e.g. slat tilting) and for different daylight scenes. The method might also be used to provide inputs for blind automation, and perhaps also as a tool for estimating the yearly energy yields from daylight in a space with automated daylight redirecting blinds.

12.2 Hierarchy of performance

The factors that can be used to describe the performance of a daylighting system can be placed on different levels. Therefore, to structure and quantify the performance of a daylighting system it is useful to apply a hierarchical approach.

As illustrated in Figure 12-1, the following categories are used, starting from the top of the hierarchy; (1) main characteristics, (2) performance criteria and (3) performance indicators. This approach has been inspired by a method developed by Andresen (2000) for evaluation of solar building design.

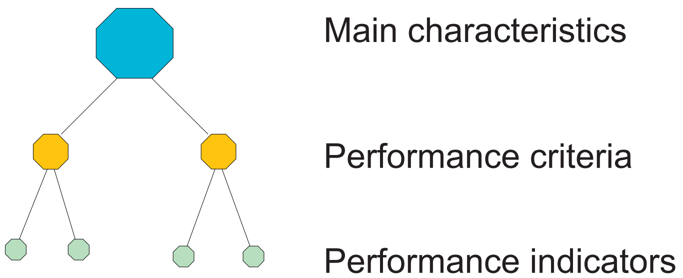


Figure 12-1 Evaluation of performance through hierarchical structuring of performance parameters.

12.3 Main performance characteristics

The objective of this section is to present the characteristics that are paramount for the performance of fenestration systems. These main characteristics should cover a range of aspects important both for the selection of a product as well as for how the system is used. Several of the paramount performance characteristics are discussed by Kuhn (Kuhn, Bühler et al. 2001). Building on the work of Kuhn, the following eight characteristics are included here as those of the highest importance for fenestration systems: visual comfort, view and privacy, thermal comfort, economy (system costs), building energy use, system reliability, hazard protection, and aesthetics.

Visual comfort addresses the need for glare protection, sufficient supply of daylight and optional room darkening.

View and privacy addresses the need for visual contact with the exterior surroundings, as well as the option to stop outsiders from looking in through the window opening.

Thermal comfort addresses the need for a thermally comfortable environment. This includes the systems ability to protect against overheating, but also utilise solar heat gains when this is desired.

Economy is always an important characteristic. Economic considerations include initial system cost and costs of operation, in relation to potential savings. Energy savings are relatively easy to document, but savings related to increased productivity of occupants and the value of a view have received increased attention (Kim and Wineman 2005).

Building energy use is gaining in importance, not only for energy cost savings, but more importantly as a result of society's desire to reduce energy consumption to save the environment. The performance of the fenestration system directly affects the energy demand for heating, cooling and lighting.

System reliability is important in that it affects the cost of operation as well as the user satisfaction.

Hazard protection addresses the need to protect against hazards such as noise, wind, fire and burglary.

Aesthetics addresses the appearance of the facade and of the fenestration system as viewed from within the building as well as from the exteriors. This could also include the aesthetic appearance of the daylight that enters into the interiors through the fenestration system

It can be argued that all of the main characteristics listed above are of importance for the overall performance of a fenestration system. However, the proposed method is focused on the performance characteristics that are influenced by the optical properties of the daylighting system. Therefore, only the first three of the main characteristics listed above are considered; (1) visual comfort, (2) view and privacy, and (3) thermal comfort.

12.4 Performance criteria

In this section the three main characteristics; (1) visual comfort, (2) view and privacy and (3) thermal comfort are discussed and performance criteria are identified for each of the performance characteristic. The performance criteria are of a subordinate level compared to the main characteristics and are used to explain and concretise the meaning of the main performance characteristics.

12.4.1 Criteria for visual comfort

Several criteria for visual comfort are discussed in the literature. Two of the most important criteria are glare protection and sufficient supply of daylight. The distribution of daylight will also influence visual comfort, and should also be included as an important criterion. These three criteria for visual comfort are discussed in the IEA sourcebook "Daylight in Buildings" (Ruck, Aschehough et al. 2000). For some applications, such as for video presentations, room darkening can be desired to obtain visual comfort. This important criterion is mentioned by Kuhn (Kuhn, Bühler et al. 2001), but has received little attention in the literature with respect to performance assessment of fenestration systems.

Based on the earlier work on visual comfort the following criteria have been identified and selected for further studies:

1. Supply of daylight
2. Room darkening
3. Light distribution
4. Glare protection

12.4.2 Criteria for view and privacy

As reported in the literature, several studies of office workers lead to the conclusion that visual contact with the exterior surroundings is one of the main positive attributes of windows (Christoffersen, Petersen et al. 1999) (Boyce, Hunter et al. 2003) (Brill, Margulis et al. 1984) (Collins 1975). Yet, visual contact with the exterior often comes at the expense of lack of privacy, and in some cases privacy protection is regarded higher than outward view. Following from this, the criteria related to view and privacy have been identified as:

5. Outward view
6. Privacy protection

12.4.3 Criteria for thermal comfort

The thermal environment can be described by physical variables such as air temperature, radiant temperature humidity and air velocity. Two important properties of windows that influence the thermal environment in building interiors are the heat transfer rate (U-value) and the solar energy transmittance (g-value).

The U-value of windows has improved significantly with modern technology involving gas-filled double or triple glazing. Most daylight redirection systems that are not physically integrated in the glazing unit will contribute little to the heat transfer rate of windows. This is especially true for modern windows with a low heat transfer rate. In addition, the heat transfer rate does not change significantly with system configurations or with the daylight scene. Therefore, in the evaluation method presented here, the performance of the daylighting system related to heat transfer rate is not considered.

Solar energy transmittance on the other hand, is strongly affected by the daylight redirection system. Solar heat can be either desired or undesired in buildings. In the heating season, a high solar energy transmittance can be desired as a supply of heat. At other times, a low solar energy transmittance can be desired for overheating protection.

Based on the above, the following two thermal comfort criteria are selected for further studies. Note that these two criteria are also important with respect to building energy use.

7. Solar heat supply
8. Overheating protection

12.4.4 Summary of performance criteria

A total of 8 different criteria have been identified and selected for further studies with respect to the performance evaluation of daylight redirection systems. The 8 criteria are summarised in Table 12-1.

Table 12-1 Selected performance criteria for daylighting systems.

Visual comfort	View and privacy	Thermal comfort
1. Supply of daylight	5. Outward view	7. Solar heat supply
2. Room darkening	6. Privacy protection	8. Overheating protection
3. Light distribution		
4. Glare protection		

12.5 Performance indicators

The complexity of identifying relevant performance criteria for fenestration systems has already been addressed. It is also a complicated task to specify good indicators for the various performance criteria. It is possible to think of a multitude of performance indicators that could be used for fenestration systems in general, and venetian blinds in particular. For some of the eight main criteria in Table 12-1, indicators have already been suggested in the literature. However, many of these indicators are related to the specific space and surroundings in which the fenestration system is used, one example of this being the daylight factor.

In the following, performance indicators for the eight performance criteria summarised in Table 12-1 are proposed and described. It has been sought to propose the indicators in a way that makes it possible to quantify them based on forward ray tracing as well as geometrical considerations and calculations. Some of the proposed indicators are comparable to those used in luminaire specification. Borrowing from the field of luminaire specification, indicators are identified so that they provide information about the function of the fenestration system itself, independently from the space and surroundings in which they are applied.

12.5.1 Supply of daylight

Several studies of office workers show that supply of daylight to the building interior is one of the major attributes of windows (Boyce, Hunter et al. 2003) (Christoffersen, Petersen et al. 1999). In addition, sufficient supply of daylight is of paramount importance for energy savings in electrical lighting.

The daylight factor has been widely used as a measure of daylight supply under overcast sky conditions (Matusiak 1998) (Christoffersen, Petersen et al. 1999) (Dubois 2001a) (Dubois 2001b) (Arnesen 2002). As described in section 2.4.1, the daylight factor is defined as the ratio of the internal illuminance at a point inside the building to the unshaded external horizontal illuminance under a CIE (traditional) overcast sky.

The daylight factor is therefore depending on the architectural space and will typically vary significantly with the geometry of the space (including size and position of windows) and also with the reflectance properties of the interiors. In effect, daylight factor studies provide information on both the quantity and distribution of diffuse light within an architectural space. As noted by Hopkinson (Hopkinson, Petherbridge et al. 1966), compared to absolute illuminance measurements, the daylight factor approach has an advantage in that it expresses the efficiency of the room as a lighting installation. Changes in outdoor lighting levels will not affect the daylight factor.

Yet it is possible to follow this line of thought one step further, and make the indicator for supply of daylight an expression of the efficiency of the fenestration system only, independent from the interior space where the system is applied.
Following from this line of thought, a simple indicator for daylight supply will be used here: the light transmittance through the fenestration system. This measure is given by the fenestration system only, and can be used for all incoming light distributions, and not only for the overcast sky. It should be noted that the light transmittance only gives information about the amount of light passing through the fenestration system, and not the distribution of the light. Indicators for light distribution are discussed in section 12.5.3.

The light transmittance describes the ratio of the total luminous flux on the interior side of the fenestration system (Φ_{int}) to the total luminous flux on the exterior side of the system (Φ_{ext}). Light transmittance of a fenestration system is calculated from equation 8.1 and is therefore straightforward to establish based on simulation results from TracePro. For more information about the light transmittance of venetian blinds it is referred to chapter 8.

12.5.2 Room darkening

The ability of a fenestration system to reduce the amount of daylight that enters into the interior can be important in many situations. One example of this is for office buildings when the space is used for a video presentation. To obtain good contrast on the projection screen, substantial room darkening might be needed. Another example is when the occupants simply prefer to reduce daylight levels to prevent the space from being perceived as too bright.

The ability of a fenestration system to provide room darkening has not been focused upon in the literature. Fixed daylighting systems (e.g. laser-cut panels and sun directing glass) generally lack this important ability.

Again, the light transmittance through the daylighting system as defined by equation 8.1 is used as a simple indicator of the systems ability to provide room darkening.

12.5.3 Light distribution

In electric lighting, a combination of direct and indirect lighting is often recommended for offices because it provides the necessary light levels on the workplane and it also reduces the contrast between the luminaire and the background and helps to avoid a gloomy appearance (CIE 1986) (Aries 2005). A similar approach is commonly used to improve visual comfort from daylight. Daylight redirection systems redirect incoming daylight towards the ceiling. In this way the uniformity of the illuminance distribution in the interiors is improved, contrasts are reduced and the room appears less gloomy. In some studies, the illuminance uniformity on the work plane is used as an indicator for the evenness of the light distribution (Moeck 1998; Dubois 2001a). This indicator is strongly dependent on factors not attributed to the fenestration system, such as the geometry of the space and the reflectance properties of the interior surfaces where the fenestration system is applied. The importance of the reflectance properties for the uniformity of illuminance can be seen from Figure 6-17.

Here a new indicator is proposed, given only by the properties of the fenestration system and the sky conditions in which it is applied. The idea is to utilise the detailed information about the light distribution that enters the interiors, as obtained from the forward ray tracing simulations. As an indicator for light distribution it is suggested to use the fraction of transmitted flux that lies within 30º from the z-axis and is also directed upwards. Or, in other words, the fraction of transmitted flux in the region marked Up 0º-30º in Figure 9-13.

The fraction of transmitted light in the Up 0º-30º region can be defined as:

$$F_{Up0-30} = \frac{\phi_{Up0-30}}{\phi_{\text{int}}} \tag{12.1}$$

Where Φ_{int} is the total luminous flux transmitted through the fenestration system.

As discussed in chapter 9, TracePro allows the user to select angular areas of interest within the luminous intensity plots, and the program can provide the total emitted flux in a given angular region. By utilising this functionality it is straightforward to obtain the fraction of transmitted flux in the Up 0º-30º region, as discussed in section 9.3.

12.5.4 Glare protection

Most fenestration systems applied in offices have the ability to prevent direct sunlight from entering into the interiors, and this will in many situations be regarded as an absolute requirement to prevent discomfort glare.

Secondly, fenestration system often influences the perceived luminance of the sky, as seen through the system. In practical studies of glare from windows, a simple approach of monitoring the average window luminance has often proved effective for predicting discomfort glare.

As discussed in chapter 10, for each and every direction, the average luminance of the window opening as observed from a long distance can be estimated by dividing the luminous intensity values by the projected area of the window opening in that direction.

When the building occupant is located near the window facade an elevated window opening will typically be positioned at a large angle above a horizontal line of sight. This might put the daylight opening outside the field of view or at least reduce the glare sensation significantly as a result of the angle between the (horizontal) line of sight and the glare source, as shown in the work of Luckiesh and Guth (1949).

Glare from an elevated daylight opening might therefore be considered more problematic when the observer is located at a long distance from the window facade, since under such conditions the daylight opening might be closer to the line of sight for a building occupant.

Based on the considerations above it is here proposed to use the average luminance of the elevated window area as a simple indicator for glare. Seen from a distant observer, the average window luminance is calculated in the direction that points towards a sky element with an elevation angle (γ) of 10º and an azimuth angle relative to the window normal ($\Delta\alpha$) of 0º. This is the same direction that was proposed and discussed in section 10.4.1. As shown in chapter 10, the average window luminance in the specified direction can be calculated from the luminous intensity plots provided by TracePro according to equation 10.1.

It is further assumed that, to avoid glare, direct sunlight should not be allowed to enter the interiors. Similarly, the presence of specular reflections from sunlight with a downward direction is a clear indication of a potential glare problem and should therefore be avoided. These two last assumptions are therefore also incorporated into the performance indicator for glare protection.

12.5.5 Outward view

The possibility for a view towards the outside surroundings is one of the main reasons for having a window. The performance of the fenestration system with respect to enabling outward viewing is therefore an important criterion. In many studies where different daylighting or shading systems are compared, their ability to provide a view have not been examined or evaluated. One important reason for this could be the lack of agreed upon criteria or standards for visibility through fenestration systems in general (Moeck, Lee et al. 1996) and through louver/blind systems in particular (Park, Augenbroe et al. 2003). This could in turn be related to the challenge of quantifying the "viewability" through a fenestration system. For example, in his otherwise comprehensive study of various daylighting systems, Möck (1998) does not consider the potential for outward viewing. The stated reason for not considering view in this study is: "due to the difficulty of separating the effects of the view window from the daylight system".

A more recent work addresses the problem of quantification of viewability through fenestration systems (Laouadi and Parekh 2007). The authors propose a view impairment index that can be calculated from luminous contrasts given by factors such as the luminances of target object and background lighting and the transmission properties of the fenestration system.

A more simple approach to quantify view is the calculation of the obstruction of view in the horizontal viewing direction, as discussed by Tzempelikos (2008).

This is very similar to the approach that has been used for louver/blind systems based on the calculation of the free view fraction (*f*), as discussed by Wirth, Gombert et al. (1998). The free view fraction is simply the fraction of the window area that allows for unobstructed view in a given direction. This seems to be a good approach for slat type fenestration systems, and the indicator for outward view used here will therefore be based on this approach.

The free view fraction can be calculated for any viewing direction. Littlefair (1996) notes that a good view is highly desirable and should normally include the foreground and the skyline. From this it seems reasonable to suggest that the horizontal direction is in general a desired direction for viewing through a window. However, upward and downward view towards the sky and ground respectively will also be desired. The viewing directions with the highest preference will most likely vary strongly depending on the scenery, as it is seen from the interiors.

Markus (1967) argues that the key characteristic of almost all views is their horizontal stratification. He divides the view in three layers, each with its own function: a layer of sky, a layer of city or landscape, and a layer of ground. The sky is the dominant light source, and gives information about the seasonal changes, time of day and weather. The distant city or landscape gives the maximum amount of information, and the view of ground gives the view a human scale. A limited view may not include all three horizontal layers. When one or two layers are blocked by obstructions the quality of the view might be lowered.

However, for a fenestration system placed in a daylight opening located above eye height, downward viewing directions are clearly not very relevant.

Based on the considerations given above, it is here proposed to use the average free view fraction in the upward directions (γ') from 0º to 45º as an indicator for evaluating the outward viewability through a slat type daylighting system.

For flat blinds with zero thickness the free view fraction for a given viewing direction can be calculated from equations 4.5 and 4.6. As can be seen, the free view fraction depends on the spacing to with ratio (*S/W*) and the slat tilt (β). The average free view fraction in viewing directions from 0º to 45º is found simply by calculating the arithmetic mean of the free view fractions in the interval from 0º to 45º.

12.5.6 Privacy protection

Privacy protection can be much desired in residential buildings, but office workers might also at times feel the need for privacy protection. The desire for privacy is often mentioned in the literature yet few studies have focused on this subject. Again, the reason might be that the degree of privacy afforded by a fenestration system is difficult to quantify. As noted by Ruck, Aschehough et al. (2000), privacy depends on the relative brightness of the interior compared to the exterior and the perception of privacy by the occupant. Privacy is also discussed by Laouadi and Parekh (2007). Here an *Indoor View Index* is introduced, calculated from luminance contrasts and the transmission properties of the fenestration system. However, as the authors comment, it should be noted that the privacy might not be a linear function of the indoor view index as privacy is inherently a subjective quantity.

The following example can be used to illustrate the difficulty in quantifying privacy: During daytime, a reflective glass (with a thin metal coating) might provide a perfectly good outward view for the building occupant, yet with no visibility from the outside towards the building interiors. At night the relative brightness is reversed. In this situation the visibility towards the interior is excellent but the possibility for an outward view is very limited. A physical approach to privacy would suggest excellent privacy protection during daytime and no privacy protection at night. However, it is reasonable to assume that the outward visibility could, to some extent, decrease the occupant's *perception* of privacy protection during the daytime, and vice versa, increase the *perception* of privacy protection at night.

It is proposed here to use the free view fraction, as discussed in the previous section, also as an indicator for privacy. Clearly, for daylighting systems located above eye height, it is the upward viewing directions (as viewed from the inside) that are the most relevant.

For the reasons given above, it is here proposed to use the maximum free view fraction in the upward directions (as viewed from inside) from 0º to 90º as an indicator for evaluating the privacy protection provided by a slat type daylighting system positioned above eye height.

For flat blinds with zero thickness the free view fraction for a given viewing direction (γ') can be calculated from equations 4.5 and 4.6. As noted in the previous section, the free view fraction depends on the spacing to with ratio (*S/W*) and the slat tilt (β). By calculating the free view fraction for every angle from 0º to 90º (in steps of 1º), the maximum free view fraction is easily obtained.

12.5.7 Solar heat supply

The total solar energy transmittance (g), as discussed in chapter 11, is often used in the quantification of solar gains through fenestration systems. It is here proposed to use the total solar energy transmittance (g) as an indicator for the solar heat supply provided by a daylighting system under a given daylight scene.

On the basis of TracePro simulations, the calculation method outlined in chapter 11 is used to provide an estimate for the g-values of different systems.

12.5.8 Overheating protection

Performance with respect to overheating protection is closely connected to solar heat gains. Therefore, the total solar energy transmittance (g) can also be used as a performance indicator with respect to overheating protection.

As above, on the basis of TracePro simulations, the calculation method outlined in chapter 11 is used to provide an estimate for the g-values of different systems.

12.6 Summary of performance indicators

The table below summarises the proposed performance indicators for the eight different performance criteria for fenestration systems located above eye height.

Table 12-2 Performance indicators for evaluation of slat type fenestration systems.

Criteria	Indicator	Symbol / equation
Supply of daylight	Total light transmittance.	$\tau = \Phi_{int} / \Phi_{ext}$
Room darkening	Total light transmittance.	$\tau = \Phi_{int} / \Phi_{ext}$
Light distribution	The fraction of the transmitted light lying in the Up 0º-30º region.	$F_{Up\_0º\text{-}30º} = \Phi_{Up\_0º\text{-}30º}/\Phi_{int}$
Glare protection	The average window luminance in the direction towards a sky element with an elevation angle (γ) of 10º and an azimuth angle relative to the window normal (Δα) of 0º.	$L_{win\_avg\_10º}$
Outward view	The average free view fraction in the upward directions from 0º to 45º.	$f_{avg\_0º\text{-}45º}$
Privacy protection	The maximum free view fraction in the upward directions from 0º to 90º.	$f_{max\_0º\text{-}90º}$
Solar heat supply	The total solar energy transmittance.	$g = \tau_{sol} + q_i$
Overheating protection	The total solar energy transmittance.	$g = \tau_{sol} + q_i$

12.7 Summary and conclusions

In this chapter a new evaluation method for daylight redirection systems with horizontal slats has been described. As emphasised in the introduction to this chapter, the main goal of the proposed method is to provide a tool that can be used to indicate the performance of a particular system with respect to all important characteristics that are determined by the optical properties of the daylighting system under a particular daylight scene.

A hierarchical approach has been used to identify the most relevant performance characteristics. The factors that can describe the performance of a daylight redirection system are structured into the following three categories: main characteristics, performance criteria and performance indicators.

Only three main characteristics are considered in this evaluation method: (1) visual comfort, (2) view and privacy and (3) thermal comfort. On the level below, eight performance criteria are identified, as shown in Table 12-1. Finally, the eight performance criteria are described by a number of performance indicators as illustrated in Table 12-2.

Some of the performance indicators are well-known from the literature, while others are modifications of previously used indicators. The indicators used for light distribution and privacy protection are novel indicators that are applied for the first time within the framework of the proposed evaluation method.

It should be noted that all of the performance indicators can be quantified either form a TracePro simulation or form geometrical considerations. This makes it possible to address a range of fundamentally different system characteristics and assess the performance of a system (or system configuration) by applying only one computer simulation program. Furthermore, it should also be noted that all of the performance indicators presented above are measurable quantities. Therefore, it is also fully possible to carry out a performance assessment of venetian blinds according to the proposed method based on physical measurements alone, without the aid of computer simulations.

In the next chapter the proposed method is utilised in order to compare the performance of white blinds and daylight redirecting blinds for different daylight scenes that are relevant for high latitudes.

13 Performance of venetian blinds in daylight openings

An ounce of performance is worth pounds of promises.

Mae West

13.1 Introduction

In the previous chapter a new evaluation method for assessing the performance of daylight redirection systems with horizontal slats was described. Some of the proposed indicators, such as light transmittance and average window luminance, have already been addressed in previous chapters while other indicators, such as the indicator for view have not been elaborated upon.

It is clear from the preceding chapters that slat reflectance properties, spacing to width ratio, as well as blind tilting affects the performance of the system in many different ways, and this makes the overall assessment of performance a complicated task.

In this chapter the new evaluation method is utilised with the aim to provide a more complete picture with respect to the performance of venetian blinds in daylight openings under different daylight scenes relevant for high latitudes.

13.2 Performance of selected systems

In this section the performance of selected venetian blind systems are presented according to the performance indicators proposed in the previous chapter. The systems are the same as those discussed in earlier chapters; a white blind in the open position (tilted for daylight admittance), a white blind in the semi-closed position (tilted at 45º) and a reflective blind in the open position (tilted for daylight redirection). Results for a reflective blind in the semi-closed position (tilted at 30º) are also provided. This is relevant under conditions when a more open blind tilt is not satisfactory, for example due to discomfort glare from the resulting high window luminance values. Finally, results are also provided for blinds that are fully closed. This can be relevant for example under conditions where overheating protection is the dominating priority. In the following tables a tilt angle (β) of 90º indicates that the slats are vertical and the blinds are completely closed. It should be noted that this configuration is not really possible in practice (for most blinds), and the results for this situation should be considered as a theoretical limit for an ideal venetian blind system.

In the following tables the white blind is indicated by a spacing to width ratio (*S/W*) of 0.9 and a diffuse slat reflectance (ρ) of 0.7 (on both slat sides). The reflective blind has a spacing to width ratio of 0.6 and a specular reflectance of 0.95 on the upper side of the slats and a diffuse reflectance of 0.4 on the lower side of the slats. These values of reflectance for the white blind are close to typical values used in traditional white blinds (see section 3.2.7). For the reflective blind it is assumed that a high quality reflector material is used on the reflective side. Today, reflector materials with a reflectance of 0.95 are commercially available and commonly used in electric lighting luminaries. On the lower side a grey surface is assumed. The use of a grey lower side is common for daylight redirecting blinds as discussed in earlier sections. Note that the reflectance of 0.4 for the grey side is higher than the value used in section 8.5. The values used here can be compared to commercially available blind slats for daylight redirecting blinds from the company Warema: These slats typically have a diffuse grey lower side with a reflectance of 33% and a specular upper side with a reflectance from 81% to 93%.

As the results show, the performance can vary strongly according to the daylight scene, and examples for all the 10 daylight scenes (summarised in Table 5-1) are provided.

13.2.1 Overcast sky

Results for overcast sky (S1) are summarised in Table 13-1 below. The first row gives the performance indicator values obtained for the double glazing without the presence of blinds. The next three rows provide results for the white blind, and the last four rows provide results for the reflective (daylight redirecting) blind.

As could be expected, the indicator for supply of daylight (τ) shows that the double glazing (without any blinds) provides the largest quantity of daylight to the interiors. The double glazing admits 74% of the incident daylight and all the configurations with blinds admit significantly less daylight. However, for the double glazing configuration, the indicator for light distribution shows that only 6.2% of the admitted light can be found in the Up 0-30 direction.

The arithmetic product of the two indicators (for daylight supply and light distribution) can be used to compare the total flux of light admitted in the Up 0-30 direction. For the double glazing (without blinds) the product is 4.6%, while for the untilted reflective blind the product is 8.7%. This interesting result show that the untilted reflective blind provides nearly twice as much light as the double glazing in the Up 0-30 direction. Internally reflected light is not considered in this comparison.

The untilted white blind admits less daylight than the untilted reflective blind and redirects a smaller fraction in the Up 0-30 direction. In addition, the average window luminance is slightly higher for the white blind, but this difference does not seem very significant since the luminances are relatively low under overcast sky conditions, even without blinds. The main positive aspect of the white blind is shown from the indicator for outward view: The average free view fraction (in the upward directions from 0º to 45º) is 0.51 for the white blind and 0.36 for the reflective blind.

It is of interest to compare the results for the white blind tilted at 45º with that of the reflective blind tilted at 30º. On a rough scale, the performance indicators predict that these two configurations are comparable with respect to all of the performance criteria under consideration. One little difference between the two is that the average window luminance is somewhat smaller for the reflective blind; 211 cd/m^2 for the reflective blind compared to 305 cd/m^2 for the white blind. Another difference is that the white blind provides slightly better, yet still quite limited, outward viewing possibilities in the horizontal and upward directions. Also, the g-value is slightly lower for the white blind; indicating a slightly better overheating protection for the white blind tilted at 45º.

Results are also provided for blinds that are fully closed (β = 90º). The most interesting indicator here is the g-value. For the fully closed white blind the calculated g-value is 0.32, while for the reflective blind it is 0.11. Overheating protection may not be the most pressing issue for overcast sky conditions, and the potential for obtaining a lower g-value is therefore typically more relevant for the scenes with direct sunlight.

Table 13-1 Performance of venetian blinds under overcast sky conditions (S1).

Blind specification			Performance indicators					
S/W	$\rho_{vis} = \rho_{sol}$	β	τ	F_{Up_0-30}	L_{win_10}	f_{avg_0-45}	f_{max_0-90}	g
	glazing		0.74	6.2%	1542	1	1	0.74
0.9	0.7d	0º	0.40	11.0%	1265	0.51	1	0.64
0.9	0.7d	45º	0.21	13.8%	305	0.04	0.21	0.51
0.9	0.7d	90º	0	N.A.	N.A.	0	0	0.32
0.6	0.95s + 0.4d	0º	0.46	18.9%	991	0.36	1	0.71
0.6	0.95s + 0.4d	30º	0.22	14.6%	211	0.01	0.17	0.61
0.6	0.95s + 0.4d	45º	0.17	9.2%	82	0	0	0.47
0.6	0.95s + 0.4d	90º	0	N.A.	N.A.	0	0	0.11

13.2.2 High sun conditions

Results for scene 8 are summarised in Table 13-2. For this daylight scene, the reflective blind tilted for sunlight redirection (β = -20°) gives the clearly best light transmittance (of the configurations with blinds), providing more than two times as much daylight to the interiors as the untilted white blind. In addition, 85% of the transmitted light lies in the Up 0º-30º region. Compared to the untilted white blind, the reflective blind provides more than 16 times more light to the Up 0º-30º region! Again, the contribution from internally reflected light is not accounted for in this comparison. The average window luminance is perhaps the most negative aspect of the reflective blind tilted for daylight redirection. For scene 8 an average window luminance of 8246 cd/m^2 is calculated. Also the white untilted blind provides a high average window luminance of 7798 cd/m^2.

If such high luminances are not acceptable, the blinds could be tilted in a more closed position. For the white blind tilted at 45º the average window luminance is 3658 cd/m^2, while for the reflective blind tilted at 30º the average window luminance is 2346 cd/m^2. It is important to note however, that at this tilt angle (β = 30º) the reflective blind has completely lost its superior performance with respect to daylight supply and light distribution. Yet, even at this tilt angle the indicators show that the performance of the reflective blind is roughly comparable to that of the white blind.

For completely closed blinds, the results show that the reflective blind provides much lower g-values than the white blind (0.12 versus 0.33). This indicates a clearly better performance potential for the reflective blind with respect to overheating protection.

Results for scene 9 are summarised in Table 13-3. The results follow the same trend as for scene 8. Again, the reflective blind tilted for daylight redirection (β = -25º) provides superior performance compared to the white blind with respect to daylight supply and light distribution. When the blinds are tilted for better glare protection (β = 30º for the reflective blind and β = 45º for the white blind) the performance is again roughly comparable for the two blinds, although the reflective blind again provides slightly lower average window luminance (1376 cd/m^2 compared to 2305 cd/m^2). When the blinds are fully closed the g-values indicate that the reflective blind has the potential to perform much better than the white blind with respect to overheating protection.

Results for scene 10 are summarised in Table 13-4. For this daylight scene the previously seen superior performance of the reflective blind with respect to daylight supply and light distribution is completely missing. The reason for this was discussed in section 8.6.5.

When the blinds are tilted for better glare protection (β = 30º for the reflective blind and β = 45º for the white blind) the performance is again roughly comparable for the two blind types.

Finally, when the blinds are fully closed the g-values again indicate that the reflective blind has the potential to perform somewhat better than the white blind with respect to overheating protection. Yet for this particular scene the difference in g-value is not quite as large as for scenes 8 and 9.

Table 13-2 Performance of venetian blinds under high sun conditions (S8).

Blind specification			Performance indicators					
S/W	$\rho_{vis} = \rho_{sol}$	β	τ	$F_{Up\_0\text{-}30}$	L_{win_10}	$f_{avg\_0\text{-}45}$	$f_{max\_0\text{-}90}$	g
	glazing		0.79	3.2%	8504	1	1	0.79
0.9	0.7d	0°	0.28	12.6%	7798	0.51	1	0.64
0.9	0.7d	45°	0.18	12.1%	3658	0.04	0.21	0.50
0.9	0.7d	90°	0	N.A.	N.A.	0	0	0.33
0.6	0.95s + 0.4d	-20°	0.67	85.0%	8246	0.61	1	0.77
0.6	0.95s + 0.4d	30°	0.13	16.2%	2346	0.01	0.17	0.57
0.6	0.95s + 0.4d	90°	0	N.A.	N.A.	0	0	0.12

Table 13-3 Performance of venetian blinds under high sun conditions (S9).

Blind specification			Performance indicators					
S/W	$\rho_{vis} = \rho_{sol}$	β	τ	$F_{Up\_0\text{-}30}$	L_{win_10}	$f_{avg\_0\text{-}45}$	$f_{max\_0\text{-}90}$	g
	glazing		0.70	4.7%	6132	1	1	0.70
0.9	0.7d	0°	0.26	14.5%	5790	0.51	1	0.57
0.9	0.7d	45°	0.17	12.8%	2305	0.04	0.21	0.46
0.9	0.7d	90°	0	N.A.	N.A.	0	0	0.31
0.6	0.95s + 0.4d	-25°	0.56	79.4%	5804	0.14	1	0.65
0.6	0.95s + 0.4d	30°	0.13	16.0%	1376	0.01	0.17	0.41
0.6	0.95s + 0.4d	90°	0	N.A.	N.A.	0	0	0.15

Table 13-4 Performance of venetian blinds under high sun conditions (S10).

Blind specification			Performance indicators					
S/W	$\rho_{vis} = \rho_{sol}$	β	τ	$F_{Up\_0\text{-}30}$	L_{win_10}	$f_{avg\_0\text{-}45}$	$f_{max\_0\text{-}90}$	g
	glazing		0.54	12.4%	4378	1	1	0.54
0.9	0.7d	0°	0.28	19.7%	3624	0.51	1	0.47
0.9	0.7d	45°	0.20	16.3%	1016	0.04	0.21	0.40
0.9	0.7d	90°	0	N.A.	N.A.	0	0	0.24
0.6	0.95s + 0.4d	-35°	0.21	6.3%	3072	0.55	1	0.49
0.6	0.95s + 0.4d	30°	0.22	16.4%	639	0.01	0.17	0.43
0.6	0.95s + 0.4d	90°	0	N.A.	N.A.	0	0	0.16

13.2.3 Intermediate sun conditions

Results for scene 5 are summarised in Table 13-5. For this daylight scene the reflective blind (tilted for sunlight redirection) again has a high light transmittance, much higher than for the white blind (tilted for sunlight cut-off). Also, the indicator for outward view predicts better viewing potential for the reflective blind than for the white blind. However, the fraction of transmitted light in the Up 0º-30º region is here relatively low. As was shown in chapter 9, the explanation for this is that most of the light is redirected in the Up 30º-60º region, providing less light transmitted in the direction towards the deeper interiors of the space. The average window luminances are here 10 241 cd/m^2 for the reflective blind and 9097 cd/m^2 for the white blind.

When the blinds are tilted in the semi-closed position (β = 30º for the reflective blind and β = 45º for the white blind) the performance is again roughly comparable for the two blinds. The average window luminances are here 5703 cd/m^2 for the reflective blind and 5156 cd/m^2 for the white blind; relatively high values for both configurations.

When the blinds are fully closed the g-values indicate that the reflective blind has the potential to perform much better than the white blind with respect to overheating protection; g = 0.09 for the reflective blind and g = 0.35 for the white blind.

Results for scene 6 are summarised in Table 13-6. Again, the reflective blind tilted for sunlight redirection (β = -10.5º) has a high light transmittance, much higher than for the white blind tilted for sunlight cut-off (β = 6.0º). Also for this scene, as for scene 5, the fraction of transmitted light in the Up 0º-30º region is relatively low (3.4%) for the reflective blind, as most of the light is redirected in the Up 30º-60º region. The average window luminances are here 6298 cd/m^2 for the reflective blind and 5913 cd/m^2 for the white blind.

Again, as for scene 5, when the blinds are tilted in the semi-closed position (β = 30º for the reflective blind and β = 45º for the white blind) the performance is roughly comparable for the two blinds. For these tilt angles the average window luminances are 3067 cd/m^2 for the reflective blind and 2806 cd/m^2 for the white blind.

When the blinds are fully closed the g-values again indicate that the reflective blind has the potential to perform much better than the white blind with respect to overheating protection.

Results for scene 7 are summarised in Table 13-7. For this scene the reflective blind (tilted for sunlight redirection) no longer has a particularly high light transmittance, and the indicators predict an overall performance that is similar to the white untilted blind. The average window luminances are here 2869 cd/m^2 for the reflective blind and 3296 cd/m^2 for the untilted white blind.

The overall performance is again roughly comparable when the two blind types are tilted in the semi-closed position (β = 30º for the reflective blind and β = 45º for the white blind). For these tilt angles the average window luminances are 528 cd/m^2 for the reflective blind and 942 cd/m^2 for the white blind.

When the blinds are fully closed the g-values indicate that the reflective blind is only slightly better (g = 0.21) than the white blind (g = 0.25) with respect to overheating protection.

Table 13-5 Performance of venetian blinds under intermediate sun conditions (S5).

Blind specification			Performance indicators					
S/W	$\rho_{vis} = \rho_{sol}$	β	τ	$F_{Up\_0\text{-}30}$	L_{win_10}	$f_{avg\_0\text{-}45}$	$f_{max\_0\text{-}90}$	g
	glazing		0.83	1.6%	13247	1	1	0.83
0.9	0.7d	20.7º	0.26	8.0%	9097	0.22	0.61	0.63
0.9	0.7d	45º	0.18	10.6%	5156	0.04	0.21	0.54
0.9	0.7d	90º	0	N.A.	N.A.	0	0	0.35
0.6	0.95s + 0.4d	1.1º	0.72	4.0%	10241	0.34	0.97	0.83
0.6	0.95s + 0.4d	30º	0.15	13.6%	5703	0.01	0.17	0.74
0.6	0.95s + 0.4d	90º	0	N.A.	N.A.	0	0	0.09

Table 13-6 Performance of venetian blinds under intermediate sun conditions (S6).

Blind specification			Performance indicators					
S/W	$\rho_{vis} = \rho_{sol}$	β	τ	$F_{Up\_0\text{-}30}$	L_{win_10}	$f_{avg\_0\text{-}45}$	$f_{max\_0\text{-}90}$	g
	glazing		0.78	2.3%	6554	1	1	0.78
0.9	0.7d	6.0º	0.29	9.3%	5913	0.41	0.88	0.63
0.9	0.7d	45º	0.17	11.1%	2806	0.04	0.21	0.50
0.9	0.7d	90º	0	N.A.	N.A.	0	0	0.33
0.6	0.95s + 0.4d	-10.5º	0.69	3.4%	6298	0.53	1	0.77
0.6	0.95s + 0.4d	30º	0.14	14.6%	3067	0.01	0.17	0.68
0.6	0.95s + 0.4d	90º	0	N.A.	N.A.	0	0	0.11

Table 13-7 Performance of venetian blinds under intermediate sun conditions (S7).

Blind specification			Performance indicators					
S/W	$\rho_{vis} = \rho_{sol}$	β	τ	$F_{Up\_0\text{-}30}$	L_{win_10}	$f_{avg\_0\text{-}45}$	$f_{max\_0\text{-}90}$	g
	glazing		0.54	7.5%	3855	1	1	0.54
0.9	0.7d	0º	0.25	15.2%	3296	0.51	1	0.46
0.9	0.7d	45º	0.16	14.3%	942	0.04	0.21	0.38
0.9	0.7d	90º	0	N.A.	N.A.	0	0	0.25
0.6	0.95s + 0.4d	-30º	0.34	3.4%	2869	0.61	1	0.51
0.6	0.95s + 0.4d	30º	0.16	14.6%	528	0.01	0.17	0.44
0.6	0.95s + 0.4d	90º	0	N.A.	N.A.	0	0	0.21

13.2.4 Low sun conditions

Results for scene 2 are summarised in Table 13-8. For this scene blind tilts of 30º for the reflective blind and 45º for the white blind are not included since these blind tilts are relatively close to the blind tilts for sunlight cut-off for the respective blind types.

When the blinds are tilted at sunlight cut-off (β = 26.8º for the reflective blind and β = 53.0º for the white blind) the reflective blind has a clearly superior performance with respect to supply of daylight (τ = 0.43 compared to τ = 0.15). However, only 2.5% of the admitted light is directed towards the Up 0º-30º region; much less than for the white blind (10.8%). This shows that for this particular daylight scene the white blind sends more daylight than the reflective blind towards the region where it is presumably needed the most. Another difference between the two is the g-value. At the sunlight cut-off tilt angle, the reflective blind provides a significantly *higher* g-value than does the white blind. The values of the other indicators are roughly comparable for the two blind types.

Again, when the blinds are fully closed, the g-value is much lower for the reflective blind (g = 0.08) than for the white blind (g = 0.34). This indicates, as before, that the reflective blind has a much better potential for overheating protection.

Results for scene 3 are summarised in Table 13-9. Also for this scene the blind tilts of 30º for the reflective blind and 45º for the white blind are not included. The performance follows exactly the same pattern as for scene 2. Again, when the blinds are tilted at sunlight cut-off (β = 22.6º for the reflective blind and β = 47.8º for the white blind) the reflective blind has a clearly superior performance with respect to supply of daylight. And again, only a small percentage of the admitted light is directed towards the Up 0º-30º region; and much less than for the white blind.

Also for this scene the g-value is much *higher* for the reflective blind than for the white blind, when both blinds are tilted for sunlight cut-off.

However, when the blinds are fully closed, the g-value is again much lower for the reflective blind than for the white blind. As before, this indicates that the reflective blind has a much better potential for overheating protection.

Results for scene 4 are summarised in Table 13-10. Also for this scene the reflective blind has a clearly superior performance with respect to supply of daylight when both blind types are tilted for sunlight cut-off. The light distribution again favours the white blind with respect to directing a larger fraction of the admitted light toward the Up 0º-30º region. However, when the higher transmittance values for the reflective blind are taken into account, this blind sends more daylight than the white blind towards the region where it is presumably needed the most.

The results for the semi-closed positions (reflective blind tilted at 30º and the white blind tilted at 45º) are here included and these results are very similar for all for the indicators, suggesting a very similar performance for the two blind types.

However, when the blinds are fully closed, as seen for all of the daylight scenes before, the reflective blind has a much better potential for overheating protection than the white blind.

Table 13-8 Performance of venetian blinds under low sun conditions (S2).

Blind specification			Performance indicators					
S/W	$\rho_{vis} = \rho_{sol}$	β	τ	$F_{Up\_0\text{-}30}$	L_{win_10}	$f_{avg\_0\text{-}45}$	$f_{max\_0\text{-}90}$	g
	glazing		0.84	0.7%	9285	1	1	0.84
0.9	0.7d	53.0º	0.15	10.8%	2211	0.01	0.11	0.53
0.9	0.7d	90º	0	N.A.	N.A.	0	0	0.36
0.6	0.95s + 0.4d	26.8º	0.43	2.5%	2141	0.03	0.25	0.80
0.6	0.95s + 0.4d	90º	0	N.A.	N.A.	0	0	0.08

Table 13-9 Performance of venetian blinds under low sun conditions (S3).

Blind specification			Performance indicators					
S/W	$\rho_{vis} = \rho_{sol}$	β	τ	$F_{Up\_0\text{-}30}$	L_{win_10}	$f_{avg\_0\text{-}45}$	$f_{max\_0\text{-}90}$	g
	glazing		0.81	0.9%	3327	1	1	0.81
0.9	0.7d	47.8º	0.16	10.2%	1644	0.03	0.18	0.53
0.9	0.7d	90º	0	N.A.	N.A.	0	0	0.34
0.6	0.95s + 0.4d	22.6º	0.46	2.1%	1309	0.06	0.36	0.78
0.6	0.95s + 0.4d	90º	0	N.A.	N.A.	0	0	0.09

Table 13-10 Performance of venetian blinds under low sun conditions (S4).

Blind specification			Performance indicators					
S/W	$\rho_{vis} = \rho_{sol}$	β	τ	$F_{Up\_0\text{-}30}$	L_{win_10}	$f_{avg\_0\text{-}45}$	$f_{max\_0\text{-}90}$	g
	glazing		0.53	3.4%	1799	1	1	0.53
0.9	0.7d	14.8º	0.20	9.3%	1152	0.29	0.72	0.44
0.9	0.7d	45º	0.12	11.2%	510	0.04	0.21	0.37
0.9	0.7d	90º	0	N.A.	N.A.	0	0	0.25
0.6	0.95s + 0.4d	-3.5º	0.45	6.1%	1430	0.43	1	0.53
0.6	0.95s + 0.4d	30º	0.12	12.3%	430	0.01	0.17	0.48
0.6	0.95s + 0.4d	90º	0	N.A.	N.A.	0	0	0.23

13.3 Summary and conclusions

Performance indicators are calculated for a reflective blind and for a white blind, both operating under10 different daylight scenes relevant for high latitudes. The results show that performance of both blind types depends strongly on the daylight scene, as well as on the mode of operation (blind tilt).

The reflective blind has the potential to supply much more daylight to the interiors than the white blind. This applies when the reflective blind is used in the open position (tilted for daylight redirection). For some of the daylight scenes the reflective blind also has a superior performance with respect to light distribution; sending a large percentage of the admitted light toward the region where it is presumably needed the most (the Up 0º-30º region). The average window luminance is an important aspect to consider when the reflective blind is tilted for daylight redirection. For many of the scenes the average window luminance is quite high. However, this is also the case for the white blind when it is operated in the open position (untilted or tilted for sunlight cut-off).

Better glare protection can generally be provided by increasing the blind tilt. In the semi-closed position, on a rough scale, the reflective blind (tilted 30º) and the white blind (tilted 45º) provide comparable values for all of the performance indicators considered.

From this it can be concluded that overall, the reflective blind can perform just as good as the white blind with respect to all of the indicators considered. In addition, for some of the daylight scenes the reflective blind has the potential for significantly superior performance with respect to daylight supply and light distribution, but utilising this superiority can result in high window luminances and potential problems with glare.

Finally, the reflective blind generally performs much better than the white blind with respect to overheating protection, provided that both blind types are kept fully closed.

14 Star diagrams

It is not in the stars to hold our destiny but in ourselves.

William Shakespeare

14.1 Introduction

The evaluation method for daylight redirection systems discussed in chapter 12 is based on the evaluation of 8 different performance criteria as given in Table 12-1. Performance indicators have been proposed, in order to indicate the performance of a daylight redirection system (or system configuration) for each of the 8 performance criteria under consideration. In chapter 13 tables that quantify the performance indicator values for different systems operating under different daylight scenes were provided. Such tables provide detailed information about performance but they may not the best way to communicate this information. In this chapter star diagrams are introduced as a means to convey the performance of various daylight redirection systems operating under different daylight scenes.

14.2 Performance rating levels

To provide a graphical illustration of the performance of daylighting redirection systems an 8-pointed star is used. Each of the 8 star points represents one of the 8 performance criteria given in Table 12-1. The length of each star point indicates the performance of the daylighting system for the corresponding criterion: a long point indicates high performance and a short point indicates low performance. The main purpose of the star diagrams is that they make the underlying information more accessible, and that looking at such diagrams can provide a quick overview of the performance of a daylight redirection system.

The performance indicators summarised in Table 12-2 are used to calculate a performance rating level from 1 (low) to 5 (high).). The performance indicator levels given in the following sections are chosen in a way that makes it possible to differentiate the performance of various typical venetian blind systems or to illustrate the difference in the performance of a given system under different daylight scenes. This implies that linear scales are not always used for the rating levels.

14.2.1 Supply of daylight

The indicator for supply of daylight is the total light transmittance through the system. The following linear indicator levels are suggested to define the rating levels from 1 (low) to 5 (high) to be used for illustrative purposes in the star diagrams:

level 1: $0.0 \leq \tau < 0.2$
level 2: $0.2 \leq \tau < 0.4$
level 3: $0.4 \leq \tau < 0.6$
level 4: $0.6 \leq \tau < 0.8$
level 5: $0.8 \leq \tau \leq 1.0$

With the suggested indicator levels, the double glazing unit (without any daylighting or shading components) will be placed in rating level 3, 4 or 5, depending on the daylight scene under consideration.

14.2.2 Room darkening

The total light transmittance is also the indicator for room darkening. It is assumed that the desired room darkening could vary significantly, depending on the situation. Therefore, the following non-linear indicator levels for light transmittance are proposed for the star diagrams:

level 1: $0.20 \leq \tau \leq 1.00$
level 2: $0.15 \leq \tau < 0.20$
level 3: $0.10 \leq \tau < 0.15$
level 4: $0.05 \leq \tau < 0.10$
level 5: $0.00 \leq \tau < 0.05$

With these indicator levels, the rating level for the double glazing with respect to room darkening is 1 for all of the 10 daylight scenes under consideration. This reflects that the double glazing unit must be considered to have a low performance with respect to providing room darkening.

14.2.3 Light distribution

The indicator for light distribution is the fraction of the transmitted light lying in the Up 0º-30º region. The following non-linear indicator levels are proposed for the star diagrams.

level 1: $0.00 \leq F_{Up\ 0º\text{-}30º} < 0.05$
level 2: $0.05 \leq F_{Up\ 0º\text{-}30º} < 0.10$
level 3: $0.10 \leq F_{Up\ 0º\text{-}30º} < 0.20$
level 4: $0.20 \leq F_{Up\ 0º\text{-}30º} < 0.40$
level 5: $0.40 \leq F_{Up\ 0º\text{-}30º} \leq 1.00$

With the suggested indicator levels, the double glazing unit (without any daylighting or shading components) will be placed in rating level 1 or 2, depending on the daylight scene under consideration. This reflects the fact that the double glazing unit itself has a low performance with respect to distribution of daylight.

14.2.4 Glare protection

The indicator for glare protection is the average window luminance in the direction towards a sky element with an elevation angle (γ) of 10º and an azimuth angle relative to the window normal (Δα) of 0º. For satisfactory glare protection it is also assumed that no direct sunlight or specularly reflected sunlight is directed downwards. For glare protection the following non-linear indicator levels are proposed for the star diagrams.

level 1: direct sunlight or downward directed specular reflections
level 2: $L_{win\_avg\_10^o} > 8000$ cd/m^2
level 3: 4000 cd/m^2 $< L_{win\_avg\_10^o} \leq 8000$ cd/m^2
level 4: 2000 cd/m^2 $< L_{win\_avg\_10^o} \leq 4000$ cd/m^2
level 5: $L_{win\_avg\_10^o} \leq 2000$ cd/m^2

With the suggested indicator levels, the double glazing unit will be placed in rating level 1 for all of the sunlight scenes (S2 – S10) and in rating level 5 for the overcast sky scene (S1). This reflects the fact that the double glazing unit itself has a low performance with respect to providing glare protection for the building occupant under direct sunlight conditions.

14.2.5 Outward view

The indicator for outward view is the average free view fraction in the upward directions from 0º to 45º. The following non-linear indicator levels for average free view fraction are proposed for the star diagrams.

level 1: $f_{avg\_0^o\text{-}45^o} = 0$
level 2: $0.0 < f_{avg\_0^o\text{-}45^o} < 0.2$
level 3: $0.2 \leq f_{avg\_0^o\text{-}45^o} < 0.5$
level 4: $0.5 \leq f_{avg\_0^o\text{-}45^o} < 1.0$
level 5: $f_{avg\_0^o\text{-}45^o} = 1$

With the suggested indicator levels, the double glazing unit (without any daylighting or shading components) will be placed in rating level 5. This reflects that the double glazing unit itself has a high performance with respect to providing outward viewing potential for the building occupants.

14.2.6 Privacy protection

The indicator for privacy protection is the maximum free view fraction in the upward directions from 0º to 90º. For this particular performance criterion it is proposed to use only two of the five indicator levels. The reason for this is that it is not straightforward to quantify or even comprehend any "moderate levels" of privacy protection. Therefore, the following indicator levels for maximum free view fraction are proposed for the star diagrams.

level 1: $f_{max\_0^o\text{-}90^o} > 0$
level 5: $f_{max\_0^o\text{-}90^o} = 0$

This implies that high privacy protection is only obtained when the window opening is completely blocked for viewing in the directions under consideration. With the suggested indicator levels, the double glazing unit (without any daylighting or shading components) will be placed in rating level 1. This illustrates, as could be expected, that the double glazing unit itself has a low performance with respect to providing privacy protection for the building occupants.

14.2.7 Solar heat supply

The indicator for solar heat supply is the total solar energy transmittance. The following linear indicator levels for solar energy transmittance are proposed for the star diagrams.

level 1: $0.0 \le g < 0.2$
level 2: $0.2 \le g < 0.4$
level 3: $0.4 \le g < 0.6$
level 4: $0.6 \le g < 0.8$
level 5: $0.8 \le g \le 1.0$

With the suggested indicator levels, the double glazing unit will be placed in rating level 3, 4 or 5, depending on the daylight scene. This reflects that the double glazing unit itself has a relatively high performance with respect to providing solar heat to the building interiors.

14.2.8 Overheating protection

The indicator for overheating protection is the total solar energy transmittance. The following non-linear indicator levels for solar energy transmittance are proposed for the star diagrams. These are the same levels that are used for classification in the standard EN 14501 (CEN 2005). The verbal description from the standard on the resulting effect on overheating protection is also included.

level 1:	$0.50 \le g \le 1.00$	very little effect
level 2:	$0.35 \le g < 0.50$	little effect
level 3:	$0.15 \le g < 0.35$	moderate effect
level 4:	$0.10 \le g < 0.15$	good effect
level 5:	$0.00 \le g < 0.10$	very good effect

With the suggested indicator levels, the double glazing unit will be placed in rating level 1 for all of the daylight scenes under consideration.

14.3 Star diagrams for selected systems and daylight scenes

In this section several examples of star diagrams are provided. The diagrams are based on the indicator levels described above and on results obtained for selected blind systems and tilt angles, as given in chapter 13. The main purpose here is to illustrate how the star diagrams can be a useful tool in the comparison of different systems, operating under different daylight scenes. Therefore, star diagrams are provided for only two of the daylight scenes; S5 (intermediate sun) and S8 (high sun).

However, in order to illustrate the flexibility of venetian blinds, star diagrams are generated for different operation modes for both the white blind and the reflective blind discussed in previous chapters.

14.3.1 Double glazing (raised blinds)

Assuming that both the white blind and the reflective blind can be raised it is of relevance to assess the performance of the double glazing unit itself. The star diagrams for daylight scenes 5 and 8 are shown in Figure 14-1 and Figure 14-2 respectively. The star diagrams illustrate the strengths and weaknesses of the double glazing unit. For both daylight scenes the double glazing unit show high performance with respect to daylight supply, outward view and solar heat supply, but a low performance with respect to all of the other performance indicators addressed.

14.3.2 Closed blinds

Most venetian blinds can be tilted to a closed position, and it is therefore of interest to provide star diagrams for blinds that are *completely* closed. As discussed earlier, this configuration is typically not possible in practice, and the results for this situation should therefore be considered as a theoretical limit for what can be achieved with the different slat materials (diffuse white or specular with high reflectance).

Star diagrams for the white and reflective blind under daylight scene 5 are given in Figure 14-3 and Figure 14-4 respectively. Star diagrams for the white and reflective blind under daylight scene 8 are given in Figure 14-5 and Figure 14-6 respectively. For the fully closed blinds no daylight is transmitted, and the daylight distribution is not relevant and no performance rating is given.

Again, the diagrams indicate a rather similar performance for the two blind types, but also here, the reflective blind is shown to provide better overheating protection.

14.3.3 Semi-closed blinds

Star diagrams for semi-closed blinds are also provided. For the white blind the tilt angle is 45º, and for the reflective blind the tilt angle is 30º. In chapter 13 it was concluded that the performance of the two blind types were comparable in the semi-closed tilt configuration. This is graphically illustrated for daylight scene 5 by the star diagrams in Figure 14-7 and Figure 14-8, and also for daylight scene 8 by the star diagrams in Figure 14-9 and Figure 14-10. The last two of these diagrams are identical.

14.3.4 Open blinds

For the white blind the open position is given by a blind tilt of 20.7º for scene 5 and untilted blind slats for scene 8. For the reflective blind the open position is given by a blind tilt of 1.1º for scene 5 and -20º for scene 8.

Star diagrams for daylight scene 5 are provided in Figure 14-11 and Figure 14-12 for the white blind and the reflective blind respectively. The star diagram for the reflective blind pinpoints the high performance with respect to supplying daylight to the interiors. However, for this daylight scene the *distribution* of the supplied daylight is clearly not the strong point of the reflective blind.

Figure 14-13 and Figure 14-14 give the star diagrams for the white and reflective blind for daylight scene 8. Again, the reflective blind is superior to the white blind with respect to supply of daylight. However, for daylight scene 8, the diagram indicates that the reflective blind also provides a superior *distribution* of the admitted daylight.

14.3.5 Star diagrams

Star diagrams for scene 5 and scene 8 are provided on the following pages.

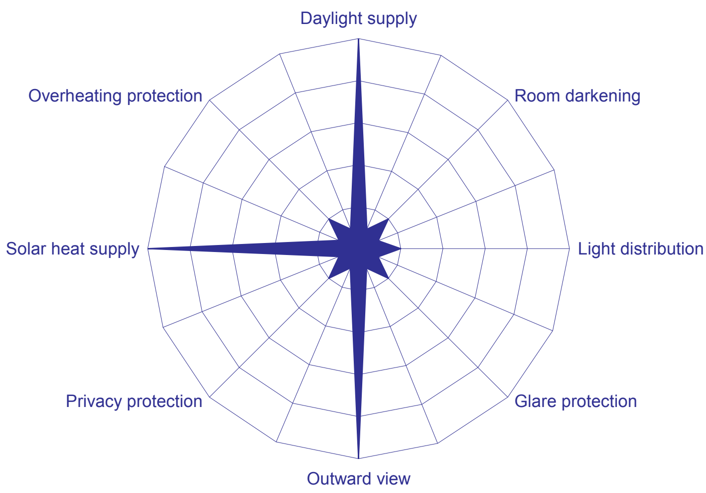


Figure 14-1 Star diagram for a double glazing unit under daylight scene 5.

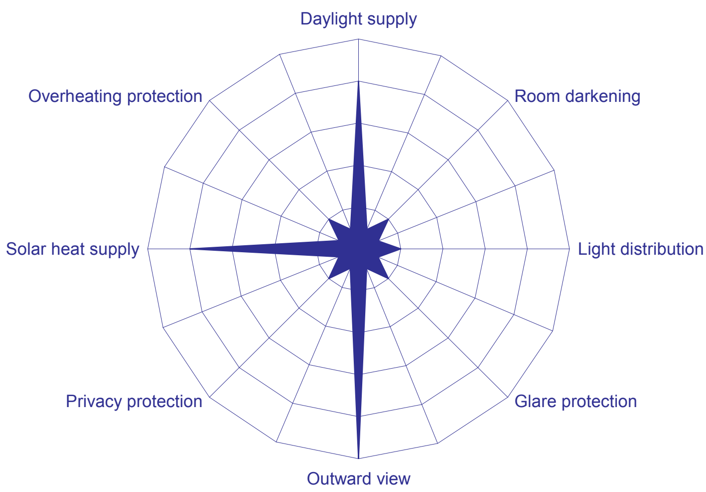


Figure 14-2 Star diagram for a double glazing unit under daylight scene 8.

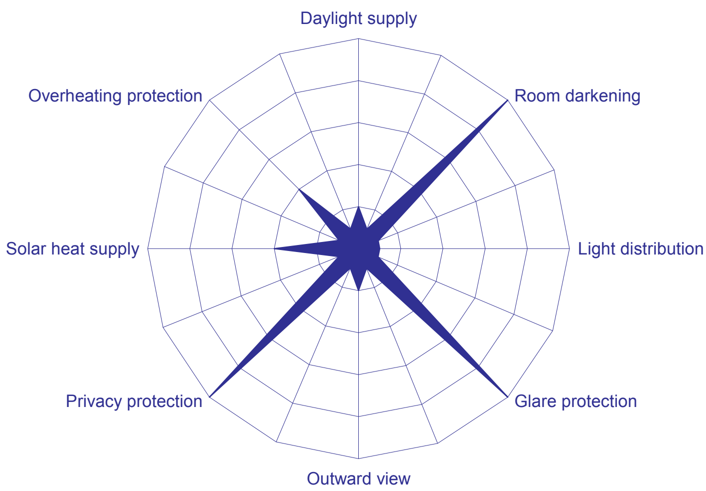


Figure 14-3 Star diagram for fully closed white blind under daylight scene 5.

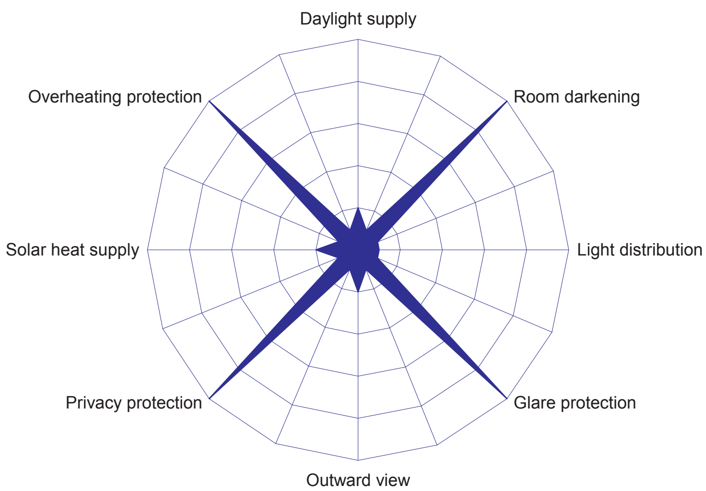


Figure 14-4 Star diagram for fully closed reflective blind under daylight scene 5.

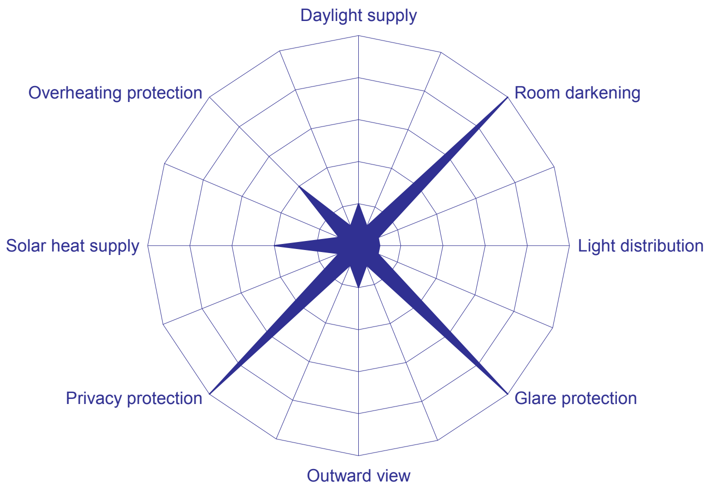


Figure 14-5 Star diagram for fully closed white blind under daylight scene 8.

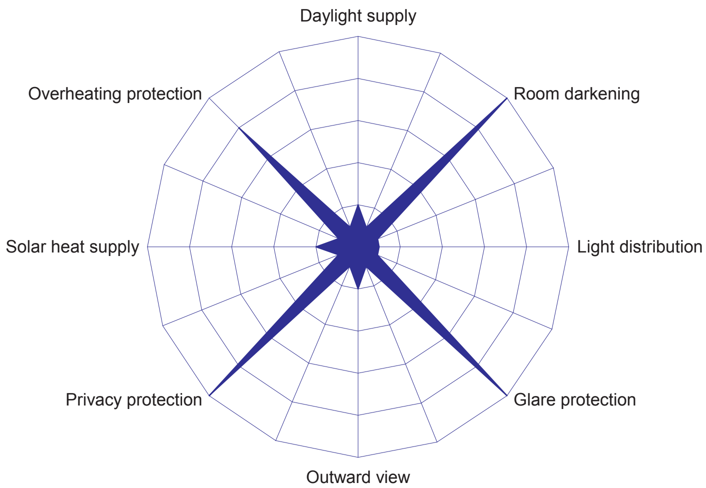


Figure 14-6 Star diagram for fully closed reflective blind under daylight scene 8.

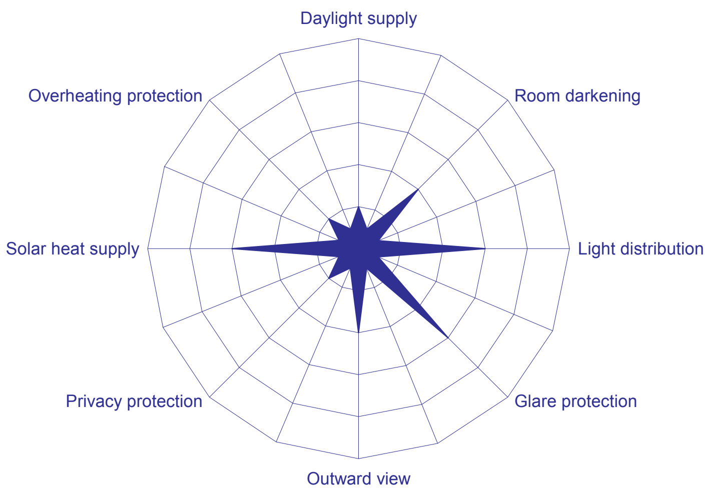


Figure 14-7 Star diagram for the semi-closed white blind under daylight scene 5.

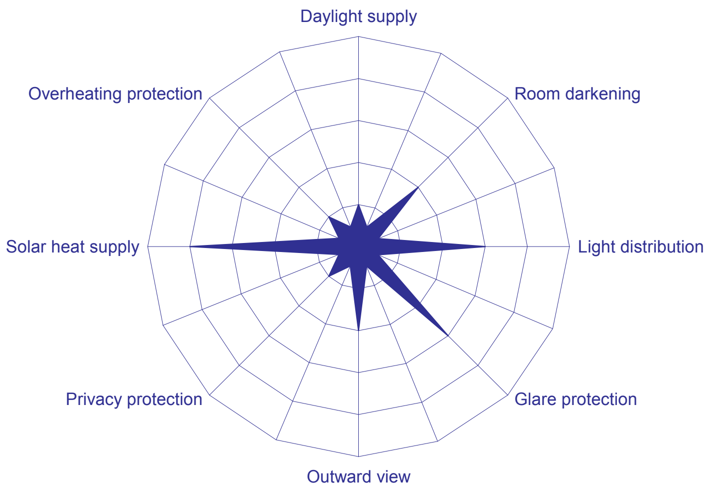


Figure 14-8 Star diagram for the semi-closed reflective blind under daylight scene 5.

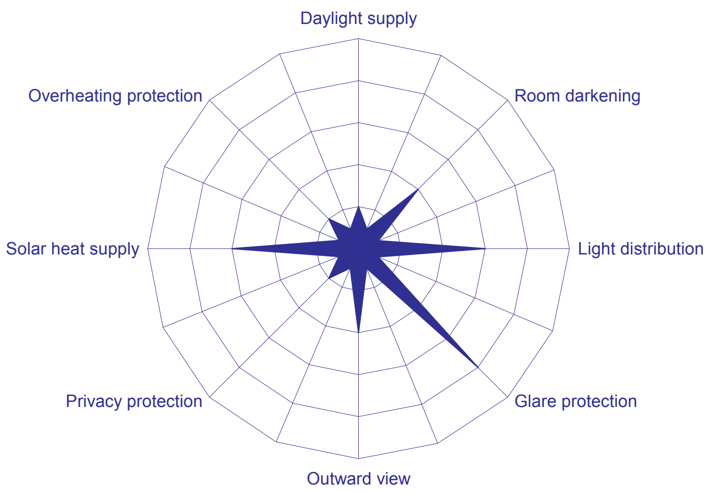


Figure 14-9 Star diagram for the semi-closed white blind under daylight scene 8.

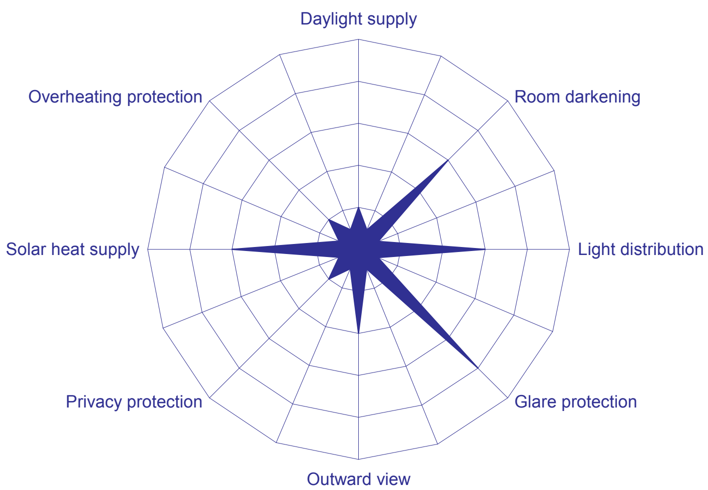


Figure 14-10 Star diagram for the semi-closed reflective blind under daylight scene 8.

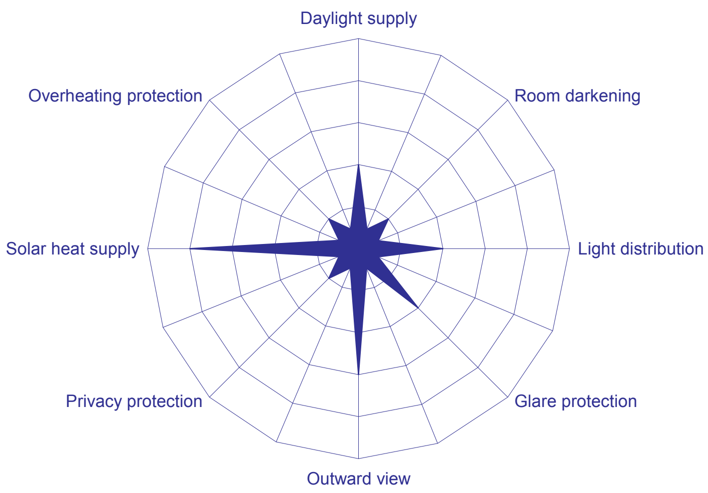


Figure 14-11 Star diagram for the open white blind under daylight scene 5.

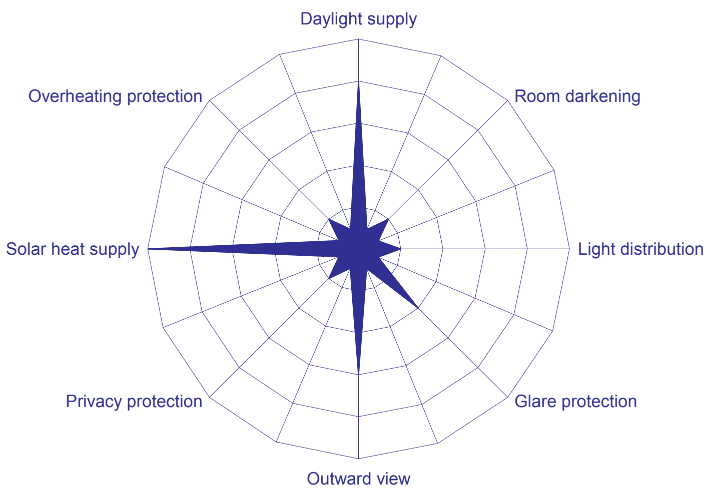


Figure 14-12 Star diagram for the open reflective blind under daylight scene 5.

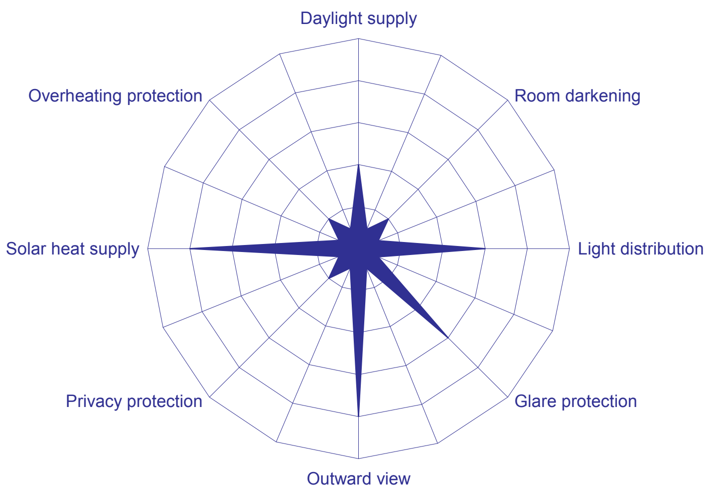


Figure 14-13 Star diagram for the open white blind under daylight scene 8.

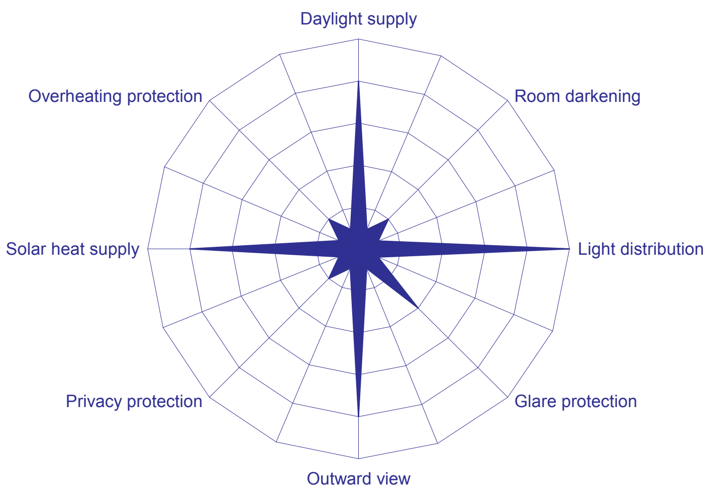


Figure 14-14 Star diagram for the open reflective blind under daylight scene 8.

14.4 Summary and conclusions

In this chapter the concept of star diagrams is introduced and described, and examples of star diagrams are given for the white blind and the reflective blind under different modes of operation. The main aim of the 8-pointed star diagram is to provide a graphical illustration of the performance of fenestration systems: each of the 8 star points represents one of the 8 performance criteria given in Table 12-1.

The star diagrams given in section 14.3.5 illustrate some of the differences between the white blind and the reflective blind. When the blinds are closed, the main difference is that the reflective blind provides superior overheating protection. When the blinds are semi-closed, the difference in performance of the two blind types is rather small. Finally, when the blinds are configured in the open position, the reflective blind shows potential for superior daylight supply and light distribution; but the performance depends strongly on the daylight scene, and high performance can not be obtained for all of the daylight scenes considered.

The star diagrams also illustrate the *flexibility* of venetian blinds. By adjusting the blind tilts the performance of the system can change considerably, and in this way it is possible to meet a variety of needs. This possibility to adjust the system performance according to varying needs is an asset that is lacking for the fixed daylight redirection systems discussed in chapter 3. For example, the laser cut panel will never be able to provide privacy protection or room darkening, even when the need for this is ever so urgent.

15 Discussion

Ideas run wild without discussion.

Serge Kahili King

15.1 Introduction

In the previous chapters results related to the performance of venetian blinds have been presented and a new evaluation method for daylight redirection systems has been proposed. In this chapter the most important findings are discussed further, with special emphasis on the new evaluation method and the performance and potential for daylight redirecting blinds.

15.2 The new evaluation method

The new evaluation method presented in chapter 12 can be used to provide information about eight performance criteria for daylight redirection systems, as given in Table 12-1:

- Supply of daylight
- Room darkening
- Light distribution
- Glare protection
- Outward view
- Privacy protection
- Solar heat supply
- Overheating protection

In order to quantify each performance criteria, a set of performance indicators are used, as given in Table 12-2.

15.2.1 Potential for the new method

A main attraction of the new evaluation method is the possibility to extract information about the simultaneous performance of several key functions of a slat-type fenestration system. Under some special conditions, one particular performance criteria of the system might be much more important than the others. With the new evaluation method it is then possible to see how this special need can be met by a particular system, or by adjusting the system (e.g. the tilt angle). At the same time, it is possible to quantify the influence this adjustment has on several other system functions.

For example, if the main desire is to admit a lot of sunlight and solar heat during the winter season, then the performance of the system with respect to these to criteria should be checked for the low sun conditions.

For most typical conditions several of the performance criteria are important at the same time. Under such conditions it is possible to assign different "weights" to the different criteria. From this an overall system performance can be calculated, and the system can be adjusted so as to maximise the overall performance.

An important potential use of the new evaluation method is for advanced building energy calculations. Today, most such calculations are carried out without taking into account the potential for energy savings that can be obtained from automatic blind operation. In the future, it is likely that more advance calculations procedures will be used, that take into account the adjustment of the blinds on an hourly basis. It is clear that such adjustments will affect the energy budget of a building with respect to both cooling, heating and lighting. The new evaluation method can be used in order to keep track of how the system performance varies, both with the daylight scene as well as with the tilt angle of the system.

Another potential use of the new method is in the development of new daylight redirection systems. The method can be used to address and quantify strengths and weaknesses of different system designs and modes of operation. With the proposed method it is also relatively straightforward to get an understanding of the performance of a new system under different relevant sky conditions. For example, if the system is to be used at locations with predominantly overcast skies and/or low sun, the performance under such conditions should be carefully addressed.

15.2.2 Limitations with respect to the type of daylighting system

The eight performance *criteria* that are addressed by the new evaluation method are relevant for all of the various types of daylight redirection systems discussed in chapter 3. It can even be argued that the eight performance criteria are relevant not only for daylight redirection systems but for fenestration systems in general.

The performance *indicators* however, put some restraints on the applicability of the new evaluation method. The performance indicators given in Table 12-2 are selected so as to be relevant for daylighting systems located at *elevated positions* in the facade, above eye height for a building occupant. This applies in particular to the indicators for glare protection, outward view and privacy protection.

15.2.3 General limitations of the new method

The proposed evaluation method is not at all intended or expected to be “the final word” for evaluation of daylight redirection systems.

First of all, it should be emphasised that the proposed method can only be used to provide information about the eight performance criteria that it addresses.

One example of an important property for fenestration systems that is not addressed by the new evaluation method is the heat transfer rate (U-value). However, it is argued here that the use of interior venetian blinds will have only a small effect on the heat transfer rate of the fenestration system. For interior venetian blinds the heat transfer rate is therefore of less significance.

The U-value of windows has improved significantly with modern technology involving gas-filled double or triple glazing. Most daylight redirection systems will contribute little to the heat transfer rate of windows. This is especially true for modern windows with a low heat transfer rate. In addition, the heat transfer rate does not change significantly with system configuration or with the daylight scene. Therefore, in the evaluation method presented in chapter 12, the performance of the daylighting system related to heat transfer rate is not considered.

Secondly, it is considered likely that other indicators could be identified that corresponds better to the main objective of characterising the performance of certain vital functions of a daylighting system. The best way to validate such new indicators is through extensive practical testing.

15.3 Performance indicators

In this section the various performance indicators used for the eight performance criteria are discussed.

15.3.1 Performance indicator for supply of daylight

The proposed indicator for supply of daylight is the total light transmittance of the system to be considered. This indicator is easy to quantify, and the importance of the total light transmittance with respect to daylight supply is difficult to question.

One significant reference for the importance of the total light transmittance is the method to predict energy savings proposed by Krarti (2005). In this method the light transmittance of the window is a key factor in the prediction of energy savings; thus emphasising the importance of this particular performance indicator.

Also, in many respects the light transmittance of daylight through a fenestration system can be compared to the light output ratio (LOR) of an electric luminaire

(CIE 1996). The LOR of a luminaire describes the ratio of the luminous flux of the luminaire to the luminous flux emitted by the electric light sources used in the luminaire. In electric lighting the light output ratio of a luminaire therefore describes how efficient (or inefficient) the luminaire is with respect to utilising the light emitted from its light sources. The LOR does not however, provide any information about the *distribution* of the light emitted from the luminaire.

In the design of energy efficient luminaires there has been a pursuit for the highest possible LOR in order to utilise the available light provided by the light sources as much as possible. One example of this trend is that high quality reflector materials have become the new standard, with light reflectance values of 95% or higher. Even a slight increase in LOR of as little as one or two percent has been highly valued by the luminaire manufacturers as well as by their customers.

In daylighting however, the importance of the light transmittance of the fenestration system, the *daylight luminaire*, has not been emphasised in a similar manner. The most obvious reason for this is that, at least so far, it has not been common practise to utilise the daylight that is available for energy savings in a controlled manner. As long as daylight utilisation is not included in the building energy budget, the performance of the fenestration with respect to daylight supply might not be sufficiently appreciated. This is rather unfortunate, considering that the luminous flux form daylight incident on a window opening is typically many times higher than that emitted from an electric light source!

15.3.2 Performance indicator for room darkening

Also for room darkening, the proposed indicator is the total light transmittance of the system to be considered. Again, the choice of indicator is rather self-explanatory.

The light transmittance has been used by several blind manufacturers to describe the ability of their blinds to block out daylight. Arguably, this has been most common for so-called blackout blinds that are specially designed to keep the interiors dark. However, as argued in section 12.5.2, the ability of the fenestration system to keep the interiors dark is relevant in many different situations.

Furthermore, since different daylighting systems might have very different properties with respect to room darkening it is useful to address this property in the performance evaluation of daylighting systems.

15.3.3 Performance indicator for light distribution

A new indicator has been proposed to indicate the performance of a daylighting system with respect to light distribution. The new indicator for light distribution is the fraction of transmitted light lying in the angular region Up 0º-30º. The main reasoning behind this is that this indicator provides information about the ability of the daylighting systems to redirect light to the regions of the interior space where it is presumably needed the most. Since the feasibility of this new indicator has not been validated in practice, a discussion about its advantages and shortcomings will be provided here.

From the literature it is clear that the ability to redirect daylight towards the ceiling is important. In this way the uniformity of the illuminance distribution in the interiors can be improved, contrasts are reduced and the room appears less gloomy than it would with a dark ceiling.

However, it is not clear exactly how much of the daylight that should be directed towards the ceiling. Would 50% be a good number, or perhaps as much as 80%? Clearly, this could vary from case to case, and no general recommendation can be given. However, it also remains clear that at least *some* redirection towards the ceiling is desired and that the clear glazing itself does not, in general, provide a good light distribution within the interiors.

In section 9.3 it is argued that the light lying in the Up 0º-30º region is assumed to reach the middle locations of the room as well as the deeper interiors. Clearly, this depends on the geometry of the room and on the location and extension of the daylight openings in the facade. For some sidelighted rooms the angular region considered here (the Up 0º-30º region) might be too limited and light lying in a broader region (for example Up 30º-45º) might contribute substantially to improve the daylight quality in the interiors. For other sidelighted rooms, the Up 0º-30º angular region might be too broad, and a stricter angular region (for example Up 0º-15º) would be more appropriate.

Naturally, the geometry of the space also has an effect on the performance of the daylighting system. For example, the reflective blind tilted in the open position provides relatively little light in the Up 0º-30º region under intermediate sun conditions, as shown in section 9.3.4. With the proposed indicator, the light distribution properties of this blind could therefore be regarded as relatively poor. However, as shown by the light distribution histograms, a large percentage of the transmitted light lies in the Up 30º-60º region. For some sidelighted spaces this might be adequate, and the light distribution properties of the reflective blind could then turn out to be excellent, even for intermediate sun positions.

Although it has been argued that it is desirable to eliminate the influence of the space in order to concentrate on the properties of the daylighting system itself; the example above clearly shows that some properties of the space cannot be completely disregarded.

Many of the advanced daylighting redirection systems discussed in chapter 3 have the ability to redirect sunlight in a non-specular manner, and thereby reduce the illuminances of the areas submitted to redirected sunlight. Perhaps the two best examples of this are the sun directing glass discussed in section 3.7 and the louver system with refractive rods discussed in section 3.3.6. These systems both have the ability to redirect sunlight not only in the vertical direction but also in the horizontal direction, in a way that provides relatively uniform illumination of the ceiling.

The proposed indicator does not provide any information about this particular ability of the daylight redirection system. With the proposed indicator there might be situations where nearly all off the admitted light is redirected towards the upper area one of the side walls, and the light can still be lying in the Up 0º-30º region. In such a situation the ceiling would mostly be lit by light that is reflected off from the wall, and one of the side walls might be significantly brighter than the other, creating unacceptable luminance ratios. Furthermore, with flat and specularly reflective blinds, the illuminances of the areas exposed to redirected light can be quite high, and this might be a cause of visual discomfort for the building occupant.

Also, the proposed indicator does not provide any information about the distribution of the light that is directed downwards. Again, unfortunate distributions of the downward directed light might cause visual discomfort and also reduce the potential for energy savings.

These shortcomings clearly illustrate that the proposed indicator for light distribution does not at all address *all* aspects that are important with respect to daylight redirection. It is therefore considered likely that other, more sophisticated indicators are needed to provide a more complete picture of the light redirection properties of a daylighting system.

Even so, it is important to realise that the luminous intensity distribution data generated by a forward ray tracing simulation contains a lot of detailed information about the distribution of the admitted light, and forward ray tracing simulations can therefore be a very useful tool in the assessment of the light distribution properties, and can also be used as a basis for new performance indicators for light distribution.

15.3.4 Performance indicator for glare protection

The proposed indicator for glare protection is the average window luminance as observed from an eye point located far from the window, when the window is observed in the direction towards a sky element with an elevation angle (γ) of 10º and an azimuth angle relative to the window normal ($\Delta\alpha$) of 0º. In addition it is also assumed that no direct sunlight is present and that no specular reflections of sunlight are directed downwards.

The assessment of glare from daylight is a very complex task. As noted in section 2.4.2 the perceived discomfort glare depends on several factors, such as the source luminance in the direction of the observers eye, the solid angle subtended by the source at the observers eye, the angular displacement of the source from the observers line of sight as well as the general field luminance controlling the adaption level of the observers eye. As a result of this complexity, the glare index formulas used to predict discomfort glare are also relatively complicated; one example being the formula proposed by Hopkinson (equation 2.1).

From this it should be immediately clear that the simplified approach of using the window luminance as a glare indicator will not produce a very accurate prediction of the perceived glare. This being said, the window luminance is still a very important factor and the ability of a fenestration system to limit the window luminances when needed is very important with respect to glare protection.

The proposed indicator gives the average window luminance when it is observed from a long distance and in an upward direction 10º above the horizontal. Since the daylighting system is assumed to be located above eye height, this direction is quite relevant for an observer located relatively far from the window. For observers located near the window, other observation directions could be more relevant. For example, for an office worker sitting on a desk near the window opening, the window luminance observed in a direction of 30º above the z-axis could perhaps be more relevant.

It should again be emphasised that the proposed indicator only gives the *average* window luminance. This means that either the sky visible behind the daylighting system or the surfaces of the daylighting system itself could be much brighter than what is indicated by the average value. The practical influence of this on the perceived glare still needs to be explored.

Also, it should be noted that glare can result not only from high window luminances, but also from bright patches of sunlight reflected off the ceiling or walls in the room. For this reason, direct sunlight or specular reflected sunlight should be avoided in order to limit the potential for discomfort glare. As discussed in the previous section, the luminous intensity distribution data generated by a forward ray tracing simulation contains a lot of detailed information about the distribution of the admitted light. Directions with particularly high luminous intensities could be a strong indication of potential glare problems. This is particularly so if the directions are downwards toward potential observers. Forward ray tracing therefore gives a unique opportunity to pinpoint observation directions that are particularly problematic, and such simulations could therefore be a very useful tool in a more detailed assessment of glare from daylight.

Again, the proposed indicator does not address all aspects of glare. It is very likely that other, more sophisticated indicators are needed in order to provide a more complete picture of the glare protection properties of a daylighting system. Still, it can be assumed that the proposed indicator can be used to provide important information about the glare properties of a daylighting system, and it is also useful for comparing different daylighting systems. Also, the new indicator can be used with benefit to provide information about how the glare properties change under different system operation modes (e.g. blind tilting) and for different sky conditions.

15.3.5 Performance indicator for outward view

A new performance indicator has been proposed for outward view; the average free view fraction in the upward viewing directions from 0º to 45º. This new indicator for viewing potential can be seen as an extension of earlier work on free view fraction or “openness fraction”, as it has also been named. The main novelty here is that several relevant viewing directions are considered and not only the horizontal viewing direction.

It follows quite naturally that upward viewing directions are the most important to consider for window openings located above the eye height of an observer. However, it is not possible to generalise about the importance of every viewing direction, as this could vary from situation to situation. Still, it has been assumed here that viewing directions from 0º and up to 45º (upwards) are the most relevant. For typical situations this includes the view of the skyline as well as a large part of the lower sky. Furthermore, the concept of the *average* free view fraction has been introduced, and all viewing directions in the interval from 0º to 45º are assumed to contribute with the same “weight”.

The perception of a view is a subjective one, and it is to be expected that the *quality* of the view through a daylighting system, or the viewing *potential* of the system will be valued differently by different observers. In order to validate the new performance indicator for outward view comprehensive practical testing needs to be carried out.

The new indicator is mainly intended to be used for slat-type daylighting systems. Furthermore, it is also assumed that the slats are opaque. For slats that are perforated, other indicators than the free view fraction should be used for outward view, since it would then be possible to obtain a limited view through the slats (even when they are fully closed). Also for other types of semi-transparent daylighting systems, for example the laser cut panel discussed in section 3.6, the free view fraction is not necessarily very relevant. If the new evaluation method is to be applied to such daylight redirection systems a more appropriate indicator for outward view should be identified.

Still, it is clear from the literature that the ability to provide a view is a very important property of a fenestration system. For flexible systems with different modes of operation such as venetian blinds, the ability to provide a view through the blind slats is therefore very important. The main idea behind the new performance indicator for outward view is to enable a rough assessment of the performance of a daylighting system with respect to outward viewing potential. In addition, the indicator can be used in order to compare the viewing potential that can be obtained from different blind types operated at different tilt angles. With this in mind the proposed indicator seems to be a good choice, at least until extensive practical testing suggests that other performance indicators are more appropriate.

15.3.6 Performance indicator for privacy protection

The perception of privacy as provided by a fenestration system is influenced by subjective factors. It seems likely, as discussed in section 12.5.6, that the *outward visibility* affects the occupants' perception of privacy protection. A good outward visibility might prevent a feeling of privacy protection even at times when the possibilities for *inward* viewing are limited. And vice versa; a poor outward visibility might at times provide a false feeling of privacy protection. From this it follows that it is not at all straightforward to quantify the performance of a fenestration system with respect to privacy protection. Still, in chapter 12 a new performance indicator has been proposed for privacy protection from slat type daylighting systems: The maximum free view fraction in the upward viewing directions from 0º to 90º.

It is considered likely that the feeling of privacy is a sort of step-function: Either you have it or you do not. For this reason, in chapter 14, only two levels of privacy protection were used. In order for the daylighting system to provide privacy protection (level 5) it needs to block the view in all upward viewing directions (as viewed from the inside). This makes it impossible for an outside observer to look down at a building occupant through the elevated window opening. It should be remarked however, that this choice of indicator opens for the possibility for an outsider to observe areas of the interior space that lie above eye height. In situations where this is considered unacceptable a stricter criterion for privacy protection could be used.

As discussed above, the perception of privacy is a subjective one, and it is to be expected that the feeling of the privacy provided by a daylighting system will be different for different observers. Therefore, in order to validate the new performance indicator for privacy protection comprehensive practical testing needs to be carried out.

15.3.7 Performance indicator for solar heat supply

The proposed indicator for solar heat supply is the total solar energy transmittance (g-value) of the system to be considered. This indicator is easy to quantify, and the importance of the g-value with respect to solar heat supply is difficult to question.

The g-value of the fenestration system is often used as a parameter in building energy calculations. For this reason the g-values when the slats are tilted at different angles are often provided by the blind manufacturers. This underlines the importance of the g-value as an indicator for solar heat supply.

15.3.8 Performance indicator for overheating protection

Overheating protection is closely related to solar heat supply. The proposed indicator for overheating protection is the same as that for solar heat supply; the total solar energy transmittance (g-value) of the system to be considered. Again, this indicator is easy to quantify, and the importance of the g-value with respect to overheating protection is difficult to question.

15.4 Star diagrams

A main objective of the star diagrams presented in chapter 14 is to convey the performance of various daylighting systems operating under different daylight scenes. For this reason it was necessary to provide a new star diagram for every daylight scene under consideration. This approach enables a graphical illustration of the performance of the system under a particular daylight scene, and also, by comparing different star diagrams, an illustration of how the performance changes for different daylight scenes. This could be important in order to illustrate how a particular system performs under a particularly important daylight scene, for example low sun conditions or overcast sky conditions.

The implication of this approach is that the star diagrams do not convey the *overall* performance of a given system. It could have been possible to expand the method in order to produce a sort of *overall* or average performance diagram for a given daylighting system. However, such an approach would require the identification of a *representative sky condition* or other assumptions about the importance of each sky type that could very well be incorrect for a particular application.

It is therefore considered better to leave it up to the user of the diagrams to decide which sky conditions are the most relevant.

For slat-type daylighting systems the performance can vary strongly with the tilt angle of the slats, or even in many cases by raising or lowering the blinds. These possibilities make slat-type systems rather flexible. It is quite straightforward to make a star diagram that expresses this flexibility by letting the diagram illustrate the *maximum potential* in performance for each of the eight performance criteria. For example, for most slat type systems excellent privacy protection can be provided simply by keeping the slats closed. Or vice versa; excellent viewing potential can be provided simply by raising the blinds.

However, it is very rare that only one system function is required. On the contrary, in most cases several needs must be met simultaneously. Therefore, it is precisely the *simultaneous capacity* of the daylighting system that is of most interest, and this is exactly what is expressed in the star diagrams in chapter 14.

In conclusion, it should be emphasised that the indicator levels used for the star diagrams are not intended to convey any assessment of the performance of a system. For example, a rating level of 3 does not mean that the performance of this particular system is “average” in any respect. As discussed in chapter 14, the performance indicator levels are chosen manly in order to make it possible to *differentiate* the performance of various typical systems or to illustrate the difference in the performance of a given system under different daylight scenes. The indicator rating levels given in chapter 14 should therefore not in any way be considered as *absolute* and other indicator rating levels may well be used when this is found more feasible.

15.5 The flexibility of venetian blinds

One of the main attractions of venetian blinds is the flexibility of operation. The blinds can be fully closed, semi-closed or tilted in an open position. Furthermore, most venetian blinds can also be raised when this is desired.

When the blinds are raised the performance will correspond to that of the window glazing itself. Normally this implies superior daylight supply and outward viewing conditions, as well as solar heat supply.

When the blinds are fully closed they provide room darkening, glare protection, privacy protection as well as some degree of overheating protection.

When the blinds are tilted in a semi-closed or open position they normally fulfil several important functions at the same time, including those of supplying daylight and of providing a better distribution of daylight within the interiors.

The possibility to tilt the slats of the blinds as well as lowering or raising the blinds sets them apart from fixed (non-adjustable) fenestration systems. With fixed systems it is neither possible to respond to changes in the daylight scene nor to the changing needs of the building occupant.

15.6 Performance and potential of daylight redirecting blinds

The literature shows that manual window blinds are operated sub-optimally, both with respect to daylight quality as well as energy saving potential. The results presented in earlier chapters seem to indicate that daylight redirecting blinds can only show their full potential when they are operated by a sophisticated automated control system. At present, there seems to be a trend towards more use of automated solutions for building energy management. This trend is likely to favour increased use of daylight redirecting blind systems in the future.

The results presented in earlier chapters show that daylight redirecting blinds in the open blind position have the potential to perform significantly better than traditional white blinds with respect to daylight supply. This applies for a broad range of typical sun positions as shown in chapter 8.

Furthermore, the daylight redirecting blinds in the open blind position also have the potential to perform much better than the traditional white blinds with respect to daylight redirection. However, with the proposed performance indicator only the light in the Up 0-30 region is assumed to contribute to daylight redirection. With this indicator the daylight redirecting properties of the daylight redirecting blind is only really superior for two of the ten daylight scenes (scene 8 and scene 9). This shows that even optimal tilting of the blinds is not necessarily enough to assure efficient daylight redirection.

In order to operate adequately, the spacing to width ratio of the daylight redirecting blind needs to be relatively small. For the blind discussed in earlier chapter the spacing to width ratio was 0.6. It is often assumed that such a narrow spacing will limit the viewing potential through the blind slats. However, for blinds located at elevated positions in the facade (above eye height) it is the upward viewing directions that are the most relevant. The results presented in earlier chapters show that the daylight redirecting blind often provides a *better* viewing potential in the upward directions compared to the traditional white blind with a spacing to width ratio of 0.9. The reason for this is that the blind with a higher *S/W* needs to be *more tilted* in order to provide sunlight cut-off.

The main problem with keeping the blinds in the open position is that this can lead to high window luminance values and thus potential glare problems. This applies both for the traditional white blind as well as for the daylight redirecting blind. However, this negative effect seems to be more problematic for the daylight redirecting blind since in this case it is more important to keep the blind in the open position in order to enhance the performance with respect to daylight supply and daylight distribution.

If it is necessary to operate the blinds in the semi-closed position in order to reduce glare, the superior performance of the daylight redirecting blind is lost. Still, the results show that the performance of the daylight redirecting blind is no worse than that of the traditional white blind when both blind types are operated in the semi-closed position.

With respect to glare protection, an important question remains unanswered. It is shown that the operation of the blinds in the open position can lead to relatively high average window luminances, particularly for intermediate and high sun scenes. For the daylight redirecting blind the average window luminance in the specified direction given by the performance indicator for glare is 8246 cd/m^2 for scene 8 and 10241 cd/m^2 for scene 10. These values are much higher than the values generally accepted to be tolerable in order to avoid discomfort glare from windows (less than 2500 cd/m^2). However, it is important to realise that these daylight redirecting blinds are assumed to be located at elevated positions above the eye height of the building occupant. At such a location higher window luminances might be tolerated. It can be assumed that the acceptable window luminance from a window opening located above eye height will depend on several factors, including the personal responses of the particular user of the space as well as on how the space is used. Further research is needed in this field in order to identify acceptable limits to window luminance for elevated window openings.

Finally, one of the most positive characteristics of the daylight redirecting blind is the performance with respect to overheating protection. As a result of the high surface reflectance, the g-value of the daylight redirecting blind is much lower than that of the traditional white blind, assuming that both blind types are operated in the closed blind position.

15.7 Performance of blinds with non-idealised slats

The results obtained and presented in earlier chapters are for blind systems with flat slats with zero thickness and idealised surface reflectance properties; either completely specular or completely diffuse. In reality, most blinds have slats that are curved, and the slat surfaces have mixed reflectance (partly diffuse and partly specular). Also, the slat thickness is obviously not zero in practice. This means that the performance of the blinds will differ from that of the idealised blinds considered here.

No calculations or simulations have been carried out on the various configurations possible for non-idealised blinds. Still, it is possible to predict some of the implications related to the performance of such non-idealised blinds.

15.7.1 Slat thickness

Most blinds have slats with a thickness that is relatively small compared to the slat width or the spacing between the slats. For these blinds it is safe to assume that the thickness of the blind slats will have a negligible influence on the optical performance of the blinds. However, some blind systems have slats with a substantial thickness. One example of this is the Fish system (discussed in section 3.3.2). For such systems the performance would of course be very different compared to a system with thin slats. Therefore, the exact geometry of the system should be modelled in order to predict the performance of the system by simulations. When the geometry of the system is known, this type of modelling is straightforward to accomplish in TracePro. All of the performance indicators given in Table 12-2 are still relevant. For blinds with thick slats, the equations used to predict outward view and privacy protection should be modified in order to take into account the slat thickness.

15.7.2 Slat curvature

Nearly all venetian blinds are provided with slats that are curved, but the degree of slat curvature varies substantially. The curvature of the slats will alter the performance of the blind system compared to the performance obtained with flat slats. However, when the slats are only slightly curved, as is common practice for most venetian blinds, the performance will not change dramatically.

All of the performance indicators given in Table 12-2 are still relevant with curved slats. But also here, the equations used to predict outward view and privacy protection would have to be modified in order to take into account the curvature of the blind slats.

As a result of the slat curvature, the outward view would be slightly restricted (for a given slat tilt). Furthermore, this would have the most impact when the blind slats are tightly spaced (low *S/W*), as is typically the case for daylight redirecting blinds. This effect will reduce the viewing potential of the typical daylight redirecting blind as compared to the typical white blind with larger slat spacing. However, as long as the curvature of the blind slats is slight, this effect should not have a significant bearing on the overall conclusions.

For the typical white blind with a slight slat curvature is assumed that the curvature plays a minor role for the supply of daylight and for the distribution of the daylight within the interiors. The reason for this is that the white slat surface will diffuse the incident light and scatter it in all directions.

However, for the daylight redirecting blind with specular blind slats the situation is very different. In this case the curvature of the slats could be significant for the resulting daylight supply and for the distribution of the transmitted light. The effect of slat curvature has not been quantified with simulations. However, it is still possible to make some remarks about the effect of slat curvature for the reflective blind.

First of all, with curved slats the direct sunlight reflected off the slats will not be collimated but rather spread out in the shape of a fan.

For high sun scenes this has an impact on the tilt angles that are needed in order to avoid downward directed light. The curved slats can have a more positive tilt angle (less negative) compared to the situation with flat slats. For high sun, as indicated in Figure 15-1 this should increase the light transmittance of the system, as less of the light reflected off a slat is obstructed by the overlying slat.

For low sun conditions the situation is more complicated, as shown in Figure 15-2. Here it seems that, with curved slats, the light incident on the outer parts of the slats are less likely to be obstructed by the overlying slat, while the light incident on the inner parts of the slats are more likely to be obstructed. The total effect of this on the resulting light transmittance has not been quantified.

The fan-shaped redistribution of sunlight from a curved specular slat will also affect the *luminous intensity distribution* of the transmitted light. As discussed in section 9.3.7, this should result in a more even distribution of daylight on the ceiling (and side walls), since the redirected sunlight will be spread out over a larger area. For some of the daylight scenes discussed earlier, the curvature of the slats is assumed to influence the light distribution histograms.

For example, for high sun scenes (S8 and S9) the histograms show that for flat blind slats, a very large fraction of the transmitted light lies in the Up 0-30 region. However, with curved slats it can be assumed that some of this light would be redirected in the Up 30-60 region instead, resulting in decreased performance with respect to daylight redirection according to the proposed performance indicator.

It is also possible that for some of the daylight scenes the opposite effect will occur. For the intermediate sun scenes (S5 and S6) most of the daylight is redirected in the Up 30-60 region with flat blinds. It is quite possible that curved slats might redirect some of this light in the Up 0-30 region, and thus *increasing* the performance with respect to daylight redirection according to the suggested performance indicator.

For low sun conditions a curved slat will also affect the luminous intensity distribution. As indicated in Figure 15-2, the curved slats seem to reflect the light at a lower angle. This could result more light towards the deeper interiors and thereby change the light distribution histograms for the low sun scenes (S2, S3 and S4).

To conclude, it can be said that the curvature of the blind slats might have a significant effect on the performance of the daylight redirecting blind. In order to better understand the implications of the slat curvature further investigations and simulations should be carried out. However, as long as the slats are only slightly curved, as is customary for most daylight redirecting blinds, the overall findings and conclusions presented in the earlier chapters should still be regarded as valid.

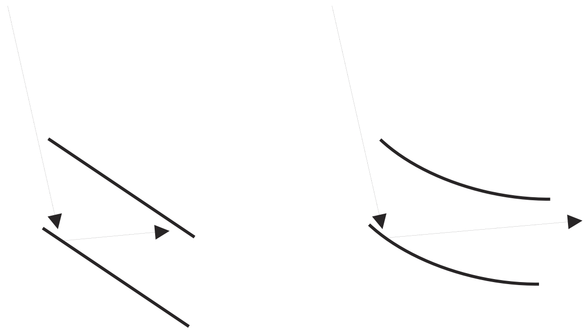


Figure 15-1 The effect of slat curvature for the reflective blind under high solar elevation. The ray path for flat slats is shown to the left and the ray path for curved slats is shown to the right.

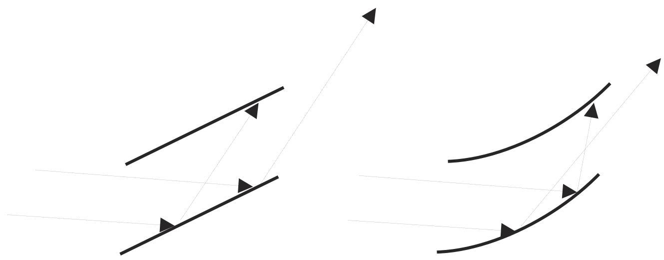


Figure 15-2 The effect of slat curvature for the reflective blind under low solar elevation. The ray path for flat slats is shown to the left and the ray path for curved slats is shown to the right.

15.7.3 Slat reflectance properties

The results obtained and presented in earlier chapters are for blind systems with idealised slats with surface reflectance properties that are either completely specular or completely diffuse. However, in reality, slats typically have surfaces showing mixed reflectance properties meaning that they are partly diffuse and partly specular. This discrepancy can influence the performance of the blind system.

Reflectance measurements for various venetian blinds are given in Figure 3-3 and Figure 3-4. The results show that there is typically a small difference between the total reflectance and the diffuse reflectance of the blind slats. This difference constitutes the specular component of the reflectance. The results for the white blind indicate that the specular component is approximately 3% in the visible region of the spectrum. This specular component, even when it is relatively small, can increase discomfort glare from the slat surface when the slats are observed in the direction of the specular reflected sunlight. Apart from this negative factor, the effect of a small specular component is considered to be limited for the other performance criteria considered here.

Vice versa, most of the commercially available specular slat materials will also have a small component of diffuse light scattering. But again, as long as the diffuse component is small, the effect on system performance is considered to be limited.

One of the positive attributes of TracePro is the possibility to accurately model and simulate the effect of the reflectance properties of a material. Measurements or mathematical descriptions of the reflectance properties of a material can be implemented into TracePro and utilised in the simulations. In this way it is straightforward to investigate the effect of applying typical slat materials with mixed reflectance properties on the system performance.

Even more interesting is the possibility to study the effect of materials with more advanced reflectance properties. For example, in electric lighting luminaries, various reflector materials have been used with reflectance properties that are tailor-made in order to accomplish a certain aim. Such materials are often classified according to their reflectance properties: semi-specular materials, semi-diffuse materials, matt materials, and so on. For daylight redirecting blinds it would be interesting to investigate the effect of a material that reflects incident light and redirects it in a cone around the specular direction. Such reflector materials are commercially available and sometimes classified as *reflectormat* materials. The idea is that the use of such a material for the slats could soften the contrasts from reflected sunlight and provide a more even light distribution on the ceiling and upper parts of the walls. At the same time, hopefully, all the positive attributes of the specular material could be kept intact. Again, the effect of such a material could readily be simulated by TracePro in order to quantify the effect on system performance.

One of the main shortcomings of the daylight redirecting blind (with specular slats) is the inability to redirect light far into the interiors when the azimuth angle of the sun is far from that of the window normal ($\Delta\alpha_s > 45°$). A slat material with reflectance properties that could reduce this shortcoming would therefore be very interesting. One possibility could be to produce a material with grooves (round, oval or v-shaped) along the z-direction. The main idea here is that light impinging on the surface of such a material would, presumably, be redirected towards the deeper interiors of a room, instead of being limited to, for example, a small area near (or on) one of the side walls. In addition, the redirected light would be spread out and distributed over a much larger interior surface area and would therefore provide a more uniform light distribution. Once again, the effect of applying such a material could readily be simulated in TracePro, and this could be an interesting area for further research.

15.8 Performance of other types of daylight redirection systems

Several different types of daylight redirection systems are discussed in chapter 3. This includes several louver and blind systems in addition to the daylight redirecting blind, such as: the Fish system, the Okasolar system and the Retrolux system. In addition other types of systems not based on louvers or blinds are also considered, including the laser cut panel and the sun-directing glass.

The new evaluation method presented in chapter 12 is primarily aimed at slat-type systems (louver and blind systems). Still, all of the performance criteria considered are also relevant for other daylight redirection systems, and most of the performance indicators given in Table 12-2 can be used directly also for other types of daylight redirection systems. Of the indicators given here it is only the free view fraction, used to predict outward view and privacy protection, which is really restricted to slat-type systems. This implies that the new evaluation method also can be used in order to provide useful information about the performance of a large range of different daylight redirection systems.

16 Conclusions

I think and think for months and years. Ninety-nine times, the conclusion is false. The hundredth time I am right.

Albert Einstein

16.1 Main objectives

The main objective of this work has been to study and document the performance characteristics of venetian blinds in a systematic manner. As given in the introduction, in section 1.3, the aim was to accomplish the following goals:

- To provide new knowledge with respect to the performance of venetian blinds in general and daylight redirecting venetian blinds in particular.
- To propose a new method for evaluation of venetian blinds located in elevated window openings in sidelighted spaces.
- To compare the performance of a traditional white venetian blind with that of a daylight redirecting (reflective) blind; both operating at high latitudes.
- To explore the possibilities in applying forward ray tracing to study various attributes that are relevant for the performance of venetian blinds.

In this concluding chapter the main findings and conclusions related to these four goals will be given. Also, in conclusion, areas for further research are suggested.

16.2 Main conclusions

Venetian blinds can be lowered or raised, and the slats can be tilted in different angles. Due to this *flexibility of operation*, the venetian blind can fulfil several important functions that are not provided by the clear glazing, such as, providing room darkening, glare protection, privacy protection, overheating protection and improved light distribution. In addition, by keeping the blinds in the open blind position or by raising the blinds, supply of daylight, solar heat supply and outward view can be promoted.

The results presented in earlier chapters show that the geometry of the blinds as well as the optical properties of the slat surface play a major role in determining the performance with respect to the various performance criteria. In addition, the daylight conditions, and especially the position of the sun relative to the daylight opening, are very important for the resulting performance.

It is important to realise that, although venetian blinds can be adjusted by tilting the slats in different angles, this operation will affect *all* of the performance criteria discussed above. It is hardly possible to fulfil all desires related to performance *simultaneously*, and this can make it problematic to establish the optimal tilt angle.

One of the benefits of the new evaluation method presented in chapter 12 is that the performance is quantified with respect to eight criteria that are important for the operation of the blind. When the blind slats are tilted in a given angle, for example in order to achieve a certain performance with respect to one particularly important performance criteria, the effect on the other performance criteria can also be seen.

The new evaluation method has been applied in order to compare the performance of traditional white blinds and daylight redirecting blinds. The results show that:

- When both blinds are operated in the semi-closed position, the performance is roughly the same for all of the performance criteria considered. This is an important result, since it shows that when the reflective blind is semi-closed, it is in no way inferior to the white blind.

- When both blind types are operated in the open blind position, the daylight redirecting blind can perform significantly better with respect to both daylight supply and light distribution. The results also show that the performance with respect to the other performance criteria is similar for the reflective blind and the white blind when both are operated in the open position. This indicates that the positive features of the reflective blind (as compared to the white blind) can be obtained without sacrificing performance in other areas.

- When the blinds are fully closed, the g-value is typically much *lower* for the reflective blind than for the white blind. This indicates that the reflective blind has a much better potential for overheating protection than the traditional white blind.

The performance of the blinds has been studied for daylight conditions that are representative for high latitudes. Previously, it has sometimes been argued that daylight redirecting blinds are less suitable at high latitudes, due to the typical low sun conditions, especially during the winter months. However, the results presented in earlier chapters show that daylight redirecting blinds can function very well under most sun conditions that are typical for high latitudes, provided that the spacing to width ratio is carefully selected.

The results only partly confirm the preliminary hypothesis. It is confirmed that a daylight redirecting blind with a specular upper slat surface has the *potential* to perform significantly better than the traditional white blind in providing useable daylight to the interiors of a sidelighted space. It is also confirmed that the relatively low sun elevations that are typical at high latitudes provide good conditions for efficient redirection of sunlight towards the deeper interiors, provided that the daylight redirecting blind is designed to operate at high latitudes. However, these benefits can not be obtained for all typical sun positions investigated. The most unfavourable conditions for the daylight redirecting blind are when the azimuth angle of the sun is far from that of the window normal.

Also, one should keep in it mind the fact that the positive effects of the reflective blind on light transmittance and light distribution are often linked to the negative effect of high window luminances.

A final goal was to explore the possibilities in applying forward ray tracing for studying various attributes that are relevant for the performance of venetian blinds. In general, it can be concluded that forward ray tracing simulations are a very useful tool in order to quantify the performance of venetian blinds. One of the drawbacks of using the software TracePro is that this software is not designed for daylighting applications. For this reason, a substantial effort was needed in order to generate light sources that represent the light form ground, sky and sun. However, once these sources were established, the many positive features of the program could be utilised with good effect in order to quantify a variety of different performance characteristics.

With the chosen performance indicators, all of the eight performance criteria addressed in the new evaluation method could be quantified either with the use of TracePro or more directly through geometrical calculations.

16.3 Further research

The work presented here is based on the results from theoretical considerations and computer simulations. No physical experiments have been carried out to validate the presented results. A natural next step is therefore to carry out practical testing. Physical measurements in real buildings or in laboratories with installed daylight redirection systems could be carried out in order to validate and expand on the theoretical findings and the proposed evaluation methods. In addition, experiments that include building occupants would be very useful in order to address the human factors. One of the key factors to establish is the seriousness of the high window luminances obtained from adjusting the blinds to the open tilt configuration. Under what conditions are the high luminances from the daylight opening acceptable? The answer to this question is important for the overall evaluation of daylight redirecting blinds.

With respect to obtaining an even better and more detailed understanding of the performance of daylight redirecting blinds, investigations related to the curvature or shape of the slats could be carried out. Likewise, a detailed study of more realistic surface reflectance properties for the slats would be of interest. Further research in this area could potentially lead to new slat materials or surface finishes, with optical properties that could improve the performance of daylight redirecting blinds. One interesting possibility here is the introduction of slats with parallel structures (e.g. cylindrical structures) extending along the slat surfaces in the z-direction. Such structures could be used in order to redirect sunlight not only in the vertical direction but also in the horizontal direction and thus create a more uniform distribution of reflected sunlight (similar to the effect created by the sun directing glass discussed in section 3.7 and the louver system with refractive rods discussed in section 3.3.6.)

Furthermore, it would be interesting to modify the evaluation method with the aim of applying it for various other types of daylight redirection systems, such as those discussed in chapter 3.

Finally, the combination of daylight redirecting blinds with other fenestration technologies is a very interesting area for further investigations. Examples of technologies that could be combined with daylight redirecting blinds include switchable glazing, laser cut panels and solar cells. In this area there seems to be a large potential for new and innovative solutions that can add new attributes to the performance of the daylight redirecting blind. One very interesting idea is to combine daylight redirecting blinds with glazing materials that incorporate horizontal stripes of photovoltaic materials (Kolås, Fagerberg et al. 2010). The PV-stripes can contribute to glare protection by stopping direct sunlight from entering the interiors, and thereby add more freedom for tilting the blinds in tilt angles that provide a useful light distribution. In addition, the PV-stripes also decrease the average window luminance, one of the major shortcomings of the reflective blind when it is tilted for redirection of daylight.

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