Daylight utilisation in office buildings

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JENS CHRISTOFFERSEN

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Contents

Preface

This thesis is a result of the researcher training programme agreed upon in 1987 between the Research Academy, the Ministry of Housing and the Danish Building Research Institute (SBI). The author, Jens Christoffersen, M.Sc. (Civ.Eng.) commenced his studies in April 1992, and defended his thesis at a public hearing and evaluation on May 22, 1995.

On June 28, 1995, Jens Christoffersen was awarded the Ph.D. degree by the Technical University of Denmark (DTU), Thermal Insulation Laboratory (LFV). The study was conducted at the Danish Building Research Institute (SBI), Energy and Indoor Climate Division, in close collaboration with the Technical University of Denmark, Thermal Insulation Laboratory. His principal supervisor was Professor Svend Svendsen (LFV) with Senior researcher, Ph.D. Søren Aggerholm (SBI) and Senior researcher, Ph.D. Erwin Petersen (SBI) as co-supervisors.

Professor Øyvind Aschehoug from the Norwegian Institute of Technology, Dept. of Architecture, acted as adjudication committee.

The close collaboration with the Technical University of Denmark was of great benefit to the project, and the Danish Building Research Institute therefore wishes to extend particular thanks to Professor Svend Svendsen from the Thermal Insulation Laboratory. The Danish Building Research Institute also wishes to extend particular thanks to the Danish Technological Institute (DTI), Energy, who made a very valuable contribution to the project by allowing the daylight measurements to be conducted at their laboratory.

Danish Building Research Institute, November 1995
Erik Christophersen
Head of Division
Energy and Indoor Climate Division

The Author's Preface

The present report, *Daylight Utilisation in Office Buildings*, forms the principal part of the requirements for obtaining the Ph.D.-degree at the Technical University of Denmark. The supplementary reports in my native language (Norwegian), all relate to the topic of "Daylight Utilisation in Office Buildings." These are (titles in English): - Visual Comfort, - Diffuse Measurements using a Shadow Band, - Energy and Indoor Analysis. The study was conducted at the Danish Building Research Institute (SBI), Energy and Indoor Climate Division, in close collaboration with the Technical University of Denmark (DTU), Thermal Insulation Laboratory.

This Ph.D. thesis does not answer or solve all the benefits and difficulties regarding use of daylight in office buildings. The intention of the study was to evaluate qualitative and quantitative consequences of three daylighting systems, aiming at improvement of the utilisation of daylight in order to supplement and replace artificial lighting. The visual quality is only illuminated by subjective assessments of the luminous environment, glare problems and luminance distributions in the interior. The intentions and hopes with the present report are that the results, by emphasising measurements and subjective assessments, can be useful to continuous research in the field of daylight.

Special thanks to my supervisors S. Svendsen (DTU), S. Aggerholm (SBI) and E. Petersen (SBI), who made a very valuable contribution and encouragement throughout the entire course of the study. I also wish to extend a special thanks to K. Johnsen (SBI) for his patient guidance and motivation during the study. Finally, a special thanks to T. Horne for his help with "proof reading" my thesis and L. Nielsen (SBI) for excellent help serving me with all my extensive literature request.

Danish Building Research Institute, November 1995
Jens Christoffersen

Summary and Conclusions

Daylight has received increased interest in the last decade because of its aesthetic possibilities and its ability to satisfy human, biological and global, ecological needs. Daylight received in the interior, through the windows, serves the building interior with a variability in light intensity, colour and direction, constantly changing from sunrise to sunset, from day to day and season to season. Daylight is also associated with high levels of natural illuminance and the benefits of passive solar heating, but also unavoidable side effects such as risk of overheating and glare etc.

A traditional window in the building facade causes an uneven daylight distribution in the room behind, with excessively bright areas near the window and areas at the back that may appear gloomy. Innovative daylighting systems may reduce these effects and extend the use of daylight without compromising visual quality and thermal comfort. The intention of the study was to evaluate qualitative and quantitative consequences of daylighting systems, aiming at improvement of the utilisation of daylight in order to supplement and replace artificial lighting. The investigation was conducted in two sparsely furnished mock-up rooms with fixed reflectances of the floor, ceiling and side walls. The rooms, one adapted for experimental measurements, the other used as a reference room, were orientated 15 degrees west of due south with room dimensions: 3.2 m wide, 6.75 m deep, and 3.1 m high. The windows were asymmetrically located in the facade with a glazing area 1.54 m high and 2.16 m wide. The interior illuminance levels were measured in the symmetry line of the window on the work plane and on the ceiling. The measurements were conducted from May to November 1994 for three types of systems:

- Interior and exterior light shelves with a matt white and reflective finish
- Venetian blinds for seven slat positions and five different types of blinds
- Light diffusing curtain

Results of the daylight measurements

The measurements in the full-scale experimental facility showed that it was possible to assess the performance of the tested daylighting systems under real sky conditions. Although partly clouded skies are the dominant weather condition in Denmark, these conditions are excluded in the investigation due to the existence of infinite numbers of sky luminance distributions. Therefore each system was evaluated only for two sky conditions, i.e. the overcast sky and the clear sky with direct sun. The measurements conducted for the clear sky with direct sun in the summer and autumn, showed a need for extended measurements to cover additional seasons (winter), a wider range of sun positions, sky conditions and different orientations. Furthermore, all the subjective assessments were conducted by the author, which limits the general validity and necessitates additional experiments with a panel of observers to assess a more general evaluation of the qualitative aspects of implementing "new" technologies to the window envelope.

The systems were investigated to assess their ability to increase daylight penetration, improve daylight distribution, and provide the interior with shade from direct sunlight and bright sky luminances, when needed. The light shelves and the Venetian blinds shade and redistribute direct sun and diffuse skylight to the interior, while curtains shade these sky conditions. To provide a performance evaluation relative to the given sky conditions, each system was compared to the normal window of the reference room. The main criteria for use of daylight systems in climates dominated by cloudy conditions are that they must not block or reject diffuse skylight, but be movable, dynamic and cope with the sun's movement. However, measurements on overcast days, showed that *all tested daylighting systems* caused an overall reduced work plane illuminance level. Subjective evaluations also showed on overcast days, occasionally, that the room with the daylighting systems (light shelf, Venetian blinds) was experienced as being brighter than the reference room, although the resulting work plane illuminance was reduced throughout the interior. However, any system which redirects or reflects light will reduce the amount of light received in the interior due to introduction of additional losses. The only way to increase the total amount of daylight compared to traditional windows, will be by use of systems, which increase the exposure of the high luminance area near the zenith.

Interior and exterior light shelves

In the main cases of the light shelf investigations, the 0.5 m wide light shelf was positioned 2.0 m above the floor level. Two finishes of the upper surface were investigated, one matt white (diffuse) and one highly reflective.

The results showed, for an *overcast sky*, that the interior light shelf reduced the light levels by 4-25%, highest in the middle and lowest at the back of the room. The exterior light shelf reduced the light levels by 10-45%, where areas near the window were shaded (45%). For a *clear sky* with direct sun (summer and autumn), the reduction at the back of the room with the diffuse light shelf, both exterior and interior, was less (1-10%). The interior reflective light shelf (autumn) increased the light levels at the back by 14-35%. However, the light shelf allowed the sun at low sun angles to penetrate the window area and the intermediate area, through the space between the light shelf and the ceiling surface. The light shelf's lack of ability to shade the front half of the room showed that the light shelf did not satisfy one of the intentions, which reduces their applicability in Danish office buildings. Also, the potential presence of direct sunlight in the interior, striking the occupants and/or the working area will in a real setting necessitate that the sun is screened off, e.g. by Venetian blinds.

The interior light shelf caused an increased dissatisfaction compared with the exterior light shelf, since the exterior view and the overall interior perception were affected by the dominating, unfamiliar, inwardly extending feature. Therefore, "acceptable" integration of an interior light shelf in the building design must emphasise the importance of the system as a coordinated and adopted part of the window design. The subjective assessments of glare problems for the overcast and the clear sky conditions showed no general, distinct differences between the reference room and the light shelf. Interpretation of these subjective observations was merely the result of the simplified light shelf's geometry since it caused no real effect on reducing the exposure to the sky. Reflected, direct sunlight caused a distinct interior discomfort by the bright light band on the ceiling and the adjacent sidewalls with a luminance of approximately 30.000 cd/m^2 .

Venetian blinds

The Venetian blinds were investigated for 7 slat positions of the following types: reflective with small and large scaled slats, white coloured with medium scaled slats, white top and reflective underside (medium), and black coloured (medium).

The results showed, for an *overcast sky*, that the Venetian blinds in a horizontal slat position reduced the light levels by 14-74%, highest in the window area. This resulted in a more uniform variation between the brightest and darkest parts of the interior. However, the reduced light level showed an unfavourable shading effect for the overcast sky, emphasising the necessity of the system's movability, when needed. Blinds in a horizontal position showed the smallest reduction in the light level at the back compared to the other slat positions. Upward tilted Venetian blinds (-30, -45 and -60°) transmitted more light from the sky directly through the blind system, which increased the illuminance level in the window area, causing the reduction to be less (20-68%). Downward tilted Venetian blinds (+30, +45 and +60°) transmitted light primarily from the reflected exterior ground, reducing the illuminance level in the window area by 75-97%. For a *clear sky* with direct sun (autumn), only the large scaled, reflective Venetian blinds in horizontal position fulfilled the intentions of increased illuminance level at the back (5-15%). However, the reflective blinds in all slat positions caused a window luminance level above 10.000 cd/m^2, which will often be experienced as unacceptable, and thus excluding the large scaled, reflective Venetian blinds as a shading device. The white Venetian blinds with downward tilted slat angles (+45 and +60°), show an efficient and acceptable shading of the direct sun, satisfying one of the intentions. The white Venetian blinds in horizontal position reduced the light level at the back by 26-28%. Tilting the blinds upward (-30° and -45°), reduced the light level at the back of the room by 31-46% and the downward tilted blinds shaded direct sunlight partly or completely, which reduced the light level at the back by 52-84%.

The Venetian blinds caused the view-out to be interfered by the completely or partly obstructed directional view. Visual discomfort with the blinds was a result of the confusion in sorting out the interesting view from the blinds, depending on the slat angle. Tilting the Venetian blinds distracted the exterior view and generated a confusion of colour judgements of the leaves on the trees in front of the daylight laboratory. This confusion was experienced, but not always replicated, when the sky was overcast and the slat angles tilted 30° and 45° upward. An acceptable view at 3 m from the window and with the blinds in a horizontal position, was only experienced for the large and the medium scaled blinds. The small scaled reflective Venetian blinds, intended for use between two layers of glazing, increased the visual discomfort even with the slats in the horizontal position. However, direct sunlight striking the slats disrupted the view since the sun caused extremely intolerable, bright lines on the slats, exceeding 100.000 cd/m^2.

With blinds in a horizontal position, a bright sky increased window glare, because the luminance level at the slats was increased and the interior adaptation luminance reduced. Upward tilted blinds increased the visibility of the sky and increased the magnitude of glare, even when the interior adaptation luminance at the front end of the room was simultaneously raised. Depending on the distance of observation, downward tilted slat angles shaded the visible sky and reduced glare problems. Problems with reflected glare arose because direct sunlight and bright skylight were reflected off the slat surface, directly into the field of view. The magnitude of reflected glare was severe and intolerable since direct sunlight reflected off the slats, causing severe reduction of the visibility and tears in one's eyes, even when viewed 6 m from the window and looking straight at the blinds. Reflected sunlight "pictured" in the interior created additional visual distractions, since the Venetian blinds reflected bands of light at particular spatial frequencies on the ceiling and the adjacent wall. All these visual discomfort problems were reduced when the slats were tilted downward and by using a diffuse slat surface.

Light diffuse curtain

The interior curtain was semi-transparent with a shading coefficient of 0.45. The curtains are measured since they are the most traditional "shading device" used in non-domestic buildings. The results showed for an *overcast sky*, that the interior curtain reduced the light level by 60-80%, lowest at the back. For a *clear sky* with direct sun (autumn), the illuminance level at the back was reduced by 10-30%. The curtain caused increased window glare problems since the luminance of the window was 10.000 cd/m^2, the interior adaptation luminance was reduced, and the view to the outside was eliminated.

Results of the energy analysis

To investigate the advantages and the consequences of replacing artificial lighting with daylight when this is sufficient, it is necessary to perform an integrated analysis of natural daylight, artificial light, light control strategies with the energy and thermal performance of buildings using, for example, tsbi3. The simplified daylight analysis model in tsbi3 showed that, by use of normal window sizes and room dimensions, the solar light factors will often be sufficiently accurate to perform a fast, integrated analysis. The purpose of this part of the study was to examine the possibilities of reducing the energy needs for lighting and heating, by using lighting control systems and by changing the window area and U-values of windows.

A module of an office building was set for calculation of the impact of combined daylighting and artificial lighting on the thermal balance of a typical office building. For this office room, the analysis was conducted for three different glazing types where the window area varied from 15%, 25% to 40% of the floor area. The base case office module was insulated according to the new Danish Building Regulations 1995 (Danish Ministry of Housing 1995) with a double glazed, lowE coated window (U-value 1.6 W/m^2 K). The traditional double glazed window (2.8 W/m^2 K) was only used as standard of reference to the Danish Building Regulations 1982, while the vacuum window (0.8 W/m^2 K) was used as an example to meet future possible building regulations. The percentage increases or decreases of energy consumption were compared to the base case assuming 15% window area with lowE glazing and the artificial lighting switched on all day. The general lighting was adjusted according to the daylight level on the work plane for reference points at 3 m and 5.4 m from the window wall. The desired illumination level at the selected reference point was 200 lux. The Venetian blinds were regulated by means of continuous control where the blinds were drawn precisely as much as necessary to keep below the limit for solar radiation (150 W/m^2).

The simulations showed (15% window) that by use of daylight as work surface illuminance, between 27% and 62% of general lighting energy may be saved. Controlling the general lighting by an on/off or dimming control strategy according to a reference point in the middle of the room (3 m), gave saving potentials of 50% and 62%, respectively. Even though the daylight level at the back (5.4 m) was lower, daylight provided savings of 27-46% of the lighting consumption. The reduced lighting consumption by selecting the reference point at the back of the room showed the importance of lighting control strategy and position of sensor, since a significant part of the lighting energy savings may easily be lost. While lighting control will reduce the energy for electrical lighting, it will always increase energy consumption for heating because of the reduced internal loads from the lighting system. When the increase in heating energy consumption was taken into account, the total energy savings were reduced to 12-19%.

Increasing the window area (25% and 40% of the floor area) increased the transmission heat losses and the heating consumption, but it will also increase the daylight illuminance level. With on/off and dimming control strategies (3 m), the lighting saving potentials were 63% and 69% (25% window area) and 66% and 71% (40% window area), respectively. Taking into account the increased heating energy consumption reduced the total energy savings to 12-13% (25% window area) and 2% (40% window area). The reduced saving potential with increased window areas indicated that an "optimum" window size may be found, but it also shows that it is essential to provide the building with control systems that adjust and reduce unneccessary use of electric lighting. Implementing a "cost index", based on the use of natural gas for heating, showed an increased saving potential of 23-30%, which emphasises that use of a "cost index" (or environment index) may have great influence on the optimum window size. Improving the U-value of the window (0.8 W/m^2 K, vacuum window), showed that the heating and lighting consumption increased the total energy savings to 33% to 39% for the examined window areas, while the energy cost savings were 42-48%. It should be kept in mind that the energy analyses are valid for the specific office module with fixed boundary conditions and the results should therefore not be uncritically transferred to general contexts.

The simulations showed that a total reduction of 50% of the requirement for energy produced from fossil fuels, as described in the Brundtland Report, "Our Common Future," and in the Danish energy plan, Energy 2000, can be regarded as an ambitious but not unrealistic goal. However, these saving potentials are achieved by simulation of "optimal conditions" and not for real conditions, which may change the interior conditions and influences, especially, the lighting energy consumption. This calls for an extended investigation of the performance of lighting control systems and the optimal interior location of the electric lighting detectors under real sky conditions.

1. Introduction

The interest in daylighting systems and control strategies in modern commercial buildings has increased in a time where global environmental issues are of high priority. Global environmental problems are linked to the emission of CO_2 to the atmosphere from combustion of fossil fuels. The Danish Government presented in December 1988, its plan of action on the environment and development, including considerable reductions in the energy demand and more intensive use of natural gas and renewable energy [Danish Ministry of Energy 1990]. These recommendations were based on the report by the World Commission on Environment, the Brundtland Report, and of the United Nations' Environmental Perspective up to the year 2000 [Brundtland 1987]. In the report "Energy 2000", the Danish government defined short- and long-term goals of the Danish energy policy. These goals are expressed as increased thermal insulation requirements of new buildings to ensure reduction in heating demands by 25% in 1995 and 50% by the year 2000. The reductions of the energy consumption in the new Danish Building Code include the following [Aggerholm 1993]:

- To increase the required insulation standards of new buildings to ensure reduction in heat demand by 25% in 1995 and 50% by the year 2000.
- To utilise technological developments in combination with standards for maximum installed electricity power in fixed lighting installations.
- To design heating installations in new buildings for low temperature operation, and optimise the performance of combined heat and power plants and use of solar heating systems.
- To introduce an energy labelling scheme for the common household appliances.

To accomplish the perspectives in the Danish energy plan, an intelligent use of natural light in office buildings will provide a potential factor for decreasing energy produced from fossil fuels. In modern commercial buildings, light is provided mostly by daylight and partly by electric lighting. In buildings which are not supported by an electric lighting control system, the lights tend to stay on and are seldom switched off again when daylight alone is sufficient. To take full advantage of the potential energy savings, it is essential to provide the building with control systems that adjust and reduce the electric light output according to the available daylight.

The main part of the present report is to evaluate the qualitative and quantitative consequences of three daylighting systems, aiming at improvement of the utilisation of daylight in order to supplement and replace artificial lighting. The systems were investigated to assess their ability to increase daylight penetration, improve daylight distribution, and provide the interior with shade from direct sunlight and bright sky luminances.

1.1 Scope of the report

In chapters 2-4 a review is given of some of the existent background of the benefits and difficulties regarding conscious use of daylighting integrated in the building design. In chapter 2, the available daylight as a natural resource is briefly discribed. Daylight is defined as the visible part of global solar radiation emitted from the sun and received on the earth's surface. Chapter 3 describes and discusses the integration of different daylighting techniques in the window envelope, since many of these systems are developed in regions where sunlight plays a decisive role. Consequently, most daylighting systems are therefore inappropriate in climates dominated by cloudy conditions as in Denmark. In chapter 4, the concept of visual comfort is only intended to present a brief description of visual perception and comfort criteria with respect to daylight design and analysis of the luminous environment. The qualitative aspects of human requirements for the interior environment are often expressed by visual and thermal "comfort", but there are few parallels between the two comfort criteria. An optimal thermal condition is the neutral perception of the interior environment, where occupants do not feel any need for changes towards warmer or colder conditions. Unfortunately, visual comfort is a more complex parameter related to receiving messages, instead of referring to a state of neutral perception of the environment.

The main part of the present report is described in chapters 5 and 6. To take full advantage of all the benefits offered by daylighting, it was necessary to acquire a deeper understanding of the behaviour of natural light in the interior environment. The intention of the study was to evaluate the qualitative and quantitative consequences of three daylighting systems, aiming at improvement of the utilisation of daylight to supplement and replace artificial lighting. Chapter 5 describes the daylight laboratory which was built at the Danish Technological Institute. In the laboratory, the daylighting systems were investigated to assess their ability to increase daylight penetration, improve daylight distribution, and provide the interior with shade from direct sunlight and bright sky luminances. In section 5.1, the design of the daylight laboratory is described, where section 5.2 presents the monitoring equipment used and degree of accuracy of the daylight measurements conducted in the daylight laboratory. Section 5.3 shows the methods of measurements and the evaluation criteria, where improvements and disadvantages were evaluated by: percentage change in illuminance level between the daylight system relative to the reference room with an unscreened window, daylight factors, and subjective evalutions. Chapter 6 shows the results of the daylight measurements, conducted from May to November 1994, for two sky conditions, i.e. the overcast sky and the clear sky with direct sun. Section 6.1 presents the results of the light shelves, both the interior and the exterior, in 5 different positions with a white diffuse and a reflective upper surface. In section 6.2, the results of the Venetian blinds located behind the glazing are presented for 7 slat positions. The selected Venetian blinds were: reflective with small and large scaled slats, white coloured with medium scaled slats, white top and reflective under side (medium), and black coloured (medium). The last section, 6.3, presents the results of the light diffuse curtain. After the results of the measurements for each daylighting system are presented, the last sub-section describes the subjective assessments of implementing the system in the window envelope.

Chapter 7 describes selected daylight design tools, of which some are used in chapter 8 to analyse the consequences of replacing artificial lighting with daylight when this is sufficient. Chapter 8 gives a short and simplified analysis of the possible enhancement of daylight utilisation and the impact on the overall energy balance for a typical office building.

2. Daylight and Solar Radiation

Daylight, as a natural resource, is defined as the visible part of global solar radiation emitted from the sun and received on the earth's surface after diffusion, attenuation and polarisation by the composition of the atmosphere. The "visible" light, perceived by the human eye and interpreted by the brain, is defined by the Commission Internationale de l'Eclairage (CIE) as *any optical radiation capable of causing a visual sensation directly. Note! There are no precise limits for the spectral range of visible radiation since they depend upon the amount of radiant power reaching the retina and the responsivity of the observer. The lower limit is generally taken between 360 nm and 400 nm and the upper limit between 760 nm and 830 nm* [CIE 1987]. Daylight and sunlight are received in the interior environment, through the window envelope, with an undisputed positive impact on the occupants. The natural light serves the interior with a variability in light intensity, colour and direction, constantly changing from sunrise to sunset, from day to day and season to season. However, daylight is also associated with high levels of natural illuminance and the benefits of passive solar heating, but also unavoidable side effects such as risk of overheating and glare etc.

2.1 Extraterrestrial radiation

In the literature, the sun is usually described as a huge fusion reactor, where light atoms are fused into heavier atoms and in the reaction process energy is emitted by the sun. Radiation emitted from the sun's surface is usually characterised as a blackbody obeying Planck's law of emitting electromagnetic radiation. Of the emitted solar radiation from the sun, roughly 98% reaches the outer edge of the earth's atmosphere, also called extraterrestrial radiation [Robinson 1966]. The extraterrestrial radiation has an almost fixed intensity called the *solar constant* $E_{e,o}$ defined as *irradiance produced by the extraterrestrial solar radiation on a surface perpendicular to the suns's rays at the mean earth-sun distance equal to 1367 W/m²* [CIE 1987]. The broken line in Figure 2.1 illustrates the spectral distribution of extraterrestral radiation and the full line is the electromagnetic radiation reaching the earth's surface.

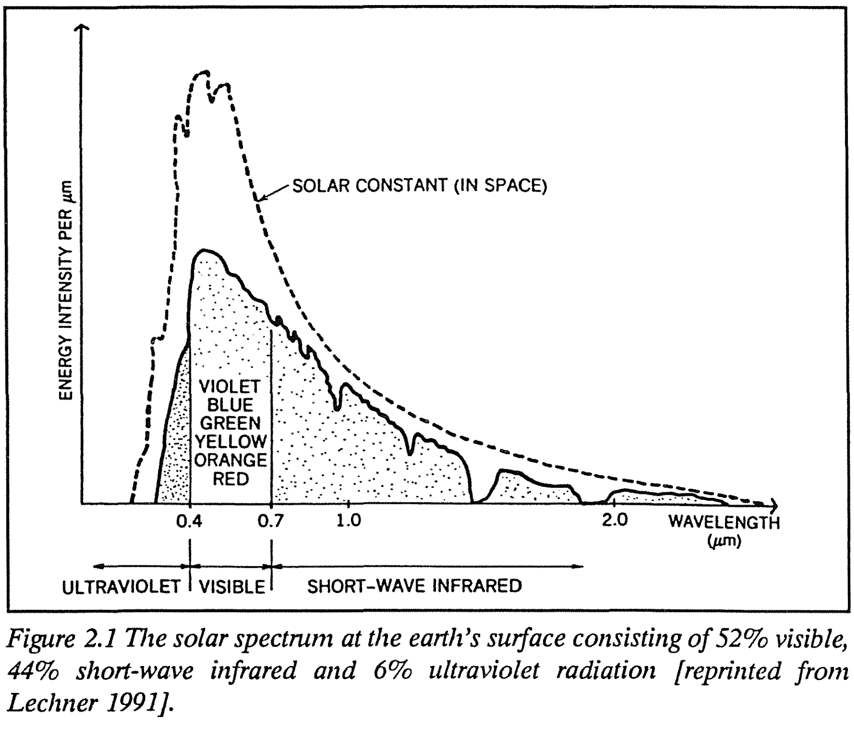


Figure 2.1 The solar spectrum at the earth's surface consisting of 52% visible, 44% short-wave infrared and 6% ultraviolet radiation [reprinted from Lechner 1991].

However, discrepancies exist in the intensity of extraterrestrial radiation emitted by the sun due to periodic variations related to sunspots (less than ± 1.5%) and the earth-sun distance. The orbit of the earth is elliptic with a variation in sun-earth distance approximately ± 1.7%, since the earth revolves around the sun and due to the eccentricity of the earth's orbit. The seasonal changes in solar radiation are a result of the sun-earth distance, where the mean sun-earth distance is equal to $1.495 \cdot 10^{11}$ m [Duffie 1991], and the earth's axis of rotation is tilted 23.45° (fixed) to the plane of the elliptical orbit. The fixed tilt of the earth's axis causes the northern hemisphere to face the sun in June at the summer solstice (June 21), when the North Pole points most closely towards the sun, and the winter solstice (December 21) when the North Pole is at its greatest distance from the sun. The spring and autumn equinoxes (March 21 and September 21) are defined as the two days of the year with equal nighttime and daytime, with sunrise and sunset due east and west, respectively.

2.2 Solar radiation at the earth's surface

The variation in intensity of solar radiation received on the earth's surface is due to changes in the extraterrestrial radiation traversing the atmosphere and the composition of the atmosphere and sky cover. Solar radiation entering the atmosphere is attenuated and polarised by atmospheric scattering in air molecules, water droplets, ice crystals, dust, and other aerosol particles in the atmosphere and by atmospheric absorption in O_3, H_2O, and CO_2. The radiation in the solar energy spectrum is attenuated, by the ozone layer in the upper atmosphere in the ultraviolet region (less than 250 nm), and by water vapour and CO_2 in the infrared region (greater than 3000 nm) [Robinson 1966, Iqbal 1983]. Figure 2.1 illustrates the electromagnetic radiation reaching the earth's surface with a spectral distribution primarily concentrated in the wavelength range of 250 to 3000 nm, where the emitted energy consist of about 52% in the visible region (380-780 nm), 44% short-wave infrared (780-3000 nm), and about 4% ultraviolet radiation ($\leq$ 380nm) [Petersen 1982].

The degree of scattering in the atmosphere is an interaction between the amount and size of the atmospheric composition and the path length of the radiation through air molecules (air mass) relative to wavelength λ of the radiation. The scattering efficiency for a clear sky depends on the wavelength according to the Rayleigh atmosphere where short wavelengths are scattered more than long wavelengths. The blue colour of a clear sky in daytime is a combination of the scattered short wavelength, the spectral distribution of sunlight together with the spectral sensitivity of the eye [Robinson 1966]. Attenuated solar radiation received on a horizontal surface is called global radiation and consist of two components, the direct solar radiation and the diffuse sky radiation. CIE has defined the two components as follows: *Direct solar radiation is the part of extraterrestrial solar radiation which as a collimated beam reaches the earth's surface after selective attenuation by the atmosphere. Diffuse sky radiation is the part of solar radiation which reaches the earth as a result of being scattered by air molecules, aerosol particles, cloud particles or other particles* [CIE 1987].

Outside the atmosphere, solar radiation is regarded as undisturbed with the beam from the sun arriving in a direct "line" with a solid cone angle of ½-degree "covering to the sun disc" (Figure 2.2). However, the spectral distribution is changed and the solar radiation is slightly scattered and attenuated in the downward traverse through the atmosphere, arriving in an apparent 5-degrees cone. The scattered radiation is called the circumsolar radiation, because it arrives centered around the sun [Balcomb 1992]. The remaining part of the radiation, the diffuse sky radiation, is scattered in all directions with a distribution depending on the specific state of the atmosphere. As a result of the forward scattering inherent in the upper atmosphere, the diffuse sky radiation is strongest around the direction to the sun. Reflections from the clouds and atmospheric constituents in the lower part of the atmosphere from the incident radiation and the ground reflected radiation, cause an increase of the diffuse sky radiation near the horizon (most pronounced for clear skies), also known as *"horizon brightening"* [Steven 1984, Duffie 1991]. The horizon brightening is more dominant at long wavelengths, whereas attenuation of the scattered radiation through the long optical path lengths near the horizon causes horizon darkening at the shorter wavelengths [Coulson 1975]. Earlier, the diffuse sky radiation was assumed to have isotropic intensity over the hemisphere (uniform sky) [Hopkinson 1966, Walsh 1961]. This assumption does not agree with new studies of the nonisotropic of scattered irradiance with its maximum close to the sun (the circumsolar region), the marked change in intensity of the sky and its distribution with different sun elevations, atmospheric turbidities and cloud cover [Perez 1987 & 1990 & 1993].

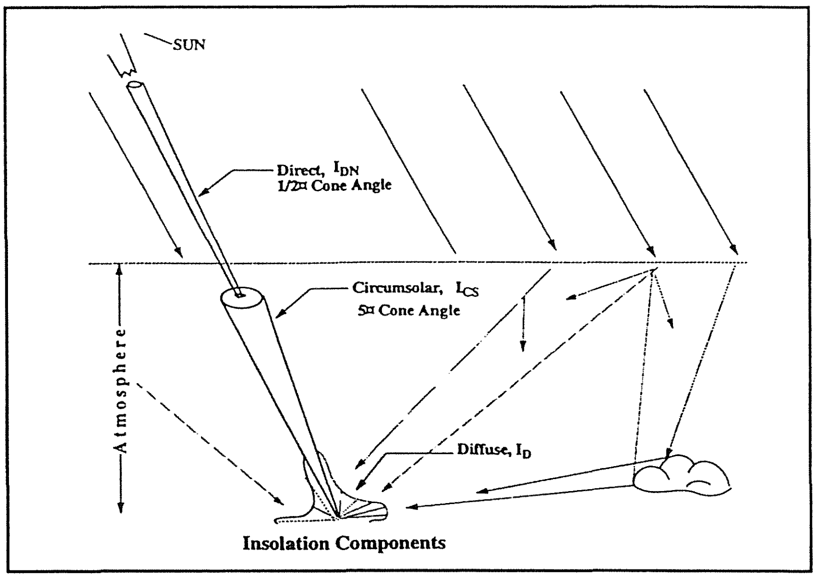


Figure 2.2 Directional distribution of solar radiation at the earth's surface [reprinted from Balcomb 1992].

2.3 Daylight

Daylight, as the visible part of solar radiation, serves the building interior with light received from direct sunlight, clear sky, clouds, and reflections from the ground causing interior variability in intensity and direction of the light admitted through the window. Resulting light from each source varies, not only in quantity, but also in quality due to extensive variability in intensity, colour and direction constantly changing during the day. This variation is one of the design parameters which are difficult to cope with, since it has great impact on both the thermal and visual environment. Reduction of the window size may provide improved control of the solar heat gain and reduced energy consumption, but it simultaneously excludes admission of daylight and external view, thus affecting the visual quality of the interior. Cautious window design is necessary, since enhanced daylight penetration may, on the other hand, also increase interior visual discomfort depending on window dimensions, location and orientation, the glazing material used, control elements applied as well as human needs and preferences.

2.3.1 Interior illuminance provided by daylight

The difficulty of defining the variation of exterior sky conditions, the change in function and characteristics of the building, has led to the development of daylighting design aids to predict the amount of daylight in the interior. The Commission Internationale de l'Eclairage (CIE) has standardised two relative luminance distributions covering the "maximum" of variation for an exterior sky condition, namely a densely overcast sky and a cloudless, clear sky. However, daylighting design according to these two normalised standard sky distributions will also, to some extent, cover situations with intermediate sky conditions. Evaluation of the amount of daylight received in the interior, using a standard sky condition, is often related to the *daylight factor* DF. The daylight factor is defined as the ratio between the interior illuminance at a given reference point on a work plane surface (normally horizontal) 0.85 m above the floor level [DS 700 1986] and the simultaneous illuminance on an exterior, unobstructed horizontal surface (overcast sky). Usually, the daylight factor is considered to contain contributions from three components - the sky component (SC), the external reflected component (ERC), and the internal reflected component (IRC) (Figure 2.3). The sky component SC is light received directly from a sky of assumed or known luminance distribution, as a function of the angle of incidence and the solid angle subtended from the interior point of the exterior visible sky, seen through the window. An external obstruction visible from the interior, directly or indirectly illuminated by the sky, is included in the external reflected component (ERC) as a fraction of the light similarly received from the obstructed patch of the sky component SC. The internal reflected component (IRC) is light received directly from internal reflecting surfaces, illuminated directly or indirectly by the sky [CIE 1987]. The daylight factor received on a horizontal surface in the interior by its component, is therefore DF = SC + ERC + IRC, as illustrated in Figure 2.3.

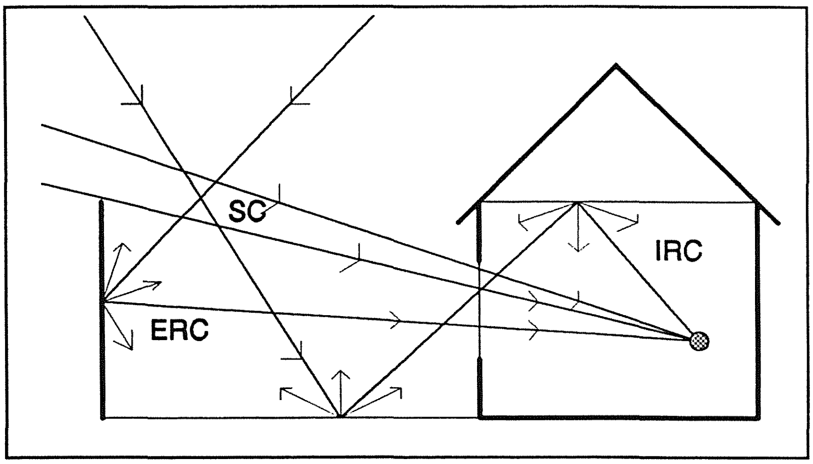


Figure 2.3 Illustration of daylight received on a horizontal surface in the interior by its components SC, ERC and IRC.

For simulation purposes, where dynamic variations of the sky conditions are taken into account, it is often more convenient to relate the illuminance at the interior reference point to the exterior illuminance on the (sloped) surface of the window. This is for instance done in the Danish thermal simulation program tsbi3, where the ratio between interior illuminance at the reference point and the exterior total illuminance on the window is called "the solar light factor SF" [Johnsen 1993 & 1994]. Because the solar light factor is split into the components of direct sun (SF1, inter-reflected component only), diffuse sky light (SF2) and reflected light from the ground and other surroundings (SF3), it varies from moment to moment. The interior illuminance can for most purposes be calculated with acceptable accuracy from hourly solar data such as the Danish Test Reference Year TRY [SBI -Report 135 1982]

2.3.2 CIE - standard daylight sky models

The light received directly from the sun is the main source of light in the interior, but this part is normally excluded in daylighting design. The sky models are described as a completely overcast sky of either uniform or non-uniform, isotropic luminance distribution and the CIE luminance distribution of the clear blue sky, with or without the sun, depends on the position of the sun and the atmospheric composition.

The simplest overcast sky model is the uniform sky, assuming the atmospheric hemisphere to have an isotropic uniform intensity over the sky vault. A uniform sky is independent of the direction of viewing or the emission of luminance [Hopkinson 1966]. The adapted CIE overcast sky model (Moon and Spencer) departs from the assumption of sky luminance uniformity and is defined as (eq. 2.1) *a completely overcast sky for which the ratio of its luminance L_γ in the direction at an angle γ above the horizon to its luminance L_Z at the zenith and direct sun is excluded* [CIE 1987]:

$$L_\gamma = L_Z \cdot \frac{1 + 2\sin\gamma}{3} \qquad 2.1$$

Both overcast sky luminance distribution models are symmetrical around the zenith, independent of the sun's position (visually undetectable sun disk and ideally diffuse atmosphere) and the azimuth angle. However, for true densely overcast conditions, the amount of the global illuminance level will depend on the cloud density and type, initial illuminance from the sun and upper sky, transmittance of the clouds, and the inter-reflection between cloud layers and between clouds and the ground [Tregenza 1982]. Estimation of the horizontal illuminanace E_h and vertical illuminance E_v can be determined for these simple sky luminance distributions by the eq. 2.2-2.3 where the effects from direct sunlight and highly reflective ground surfaces are excluded [Baker 1993]:

$$E_h = L_Z \cdot \left[\frac{2 \cdot \pi}{1 + b} \cdot \left(\frac{1}{2} + \frac{b}{3}\right)\right] \qquad 2.2$$

$$E_v = L_Z \cdot \left[\frac{1}{1 + b} \cdot \left(\frac{\pi}{2} + \frac{2 \cdot b}{3}\right)\right] \qquad 2.3$$

where	L_z	zenith luminance
	$b = 0$	uniform sky
	$b = 2$	CIE standard overcast sky

The ratio of the vertical illuminance to the horizontal illuminance is determined by eq. 2.4 and eq. 2.5:

Uniform sky:

$$\frac{E_v}{E_h} = 0.5 \qquad 2.4$$

CIE standard overcast sky:

$$\frac{E_v}{E_h} = 0.396 \qquad 2.5$$

The clear sky luminance distribution varies with the sun's position and the atmospheric composition, having brighter areas near the horizon compared to the zenith, except for the circumsolar region. The CIE - standard clear sky luminance distribution is a function of the zenith luminance of the sky, combining mean real conditions and fundamental attenuation, diffusion and scattering of direct sunlight [CIE 1973, 1994]. This ideal sky luminance distribution expresses, for a perfect cloudless atmosphere, the ratio of the luminance of a sky element $L_{vcl}(\gamma,\theta)$, modified by the apparent sun position on the sky vault and the diffusion indicatrix, to the zenith luminance L_{vclz} by eq. 2.6 [Tregenza 1993]:

$$\frac{L_{vcl}(\gamma,\theta)}{L_{vclz}} = \frac{\phi(\gamma)}{\phi\left(\frac{\pi}{2}\right)} \cdot \frac{f(\theta)}{f\left(\frac{\pi}{2} - \gamma_s\right)} \qquad 0 \le \gamma_s \le \frac{\pi}{2}, 0 < \gamma \le \frac{\pi}{2} \qquad 2.6$$

where	γ_s	solar altitude
	γ	angle of altitude above the horizon of the sky element P
	θ	angular between the sky element P and the sun (eq. 2.9).

The functions *f*:

$$\begin{aligned} f(\theta) &= 1 + N \cdot (\exp[-3 \cdot \theta] - 0.009) + M \cdot \cos^2 \theta \\ N &= 4.3 \cdot T_{il}^{1.9} \cdot [-0.35 \cdot T_{il}] \\ M &= \frac{0.71}{\sqrt{T_{il}}} \end{aligned} \qquad 2.7$$

where	T_{il}	illuminance turbidity $T_{il} = 2.45$ and 5.5, for clean and polluted atmosphere, respectively

The functions ϕ:

$$\begin{aligned} \phi(\gamma) &= 1 - \exp \cdot [\frac{-0.32}{\sin \gamma}] \\ \phi\left(\frac{\pi}{2}\right) &\approx 0.27385 \end{aligned} \qquad 2.8$$

The sky luminance distribution is symmetric around the sun meridian and its azimuth angle from the sun meridian. For clean, rural atmosphere, Linke turbidity factor equal to 2.45, is a function of the relative diffusion indicatrix [Kittler 1967] defined for the sky element by f (θ) (eq. 2.7) and for the zenith by f $(\pi/2 - \gamma_s)$ (eq. 2.7) [CIE 1973, 1994]. The angle θ between the sky element P and the sun is defined by eq. 2.9 (Figure 2.4), represented by the angle of altitude above the horizon (γ) and the difference between surface and sun azimuth angle $(\alpha_s - \alpha)$:

$$\cos\theta = \sin\gamma_s \cdot \sin\gamma + \cos\gamma_s \cdot \cos\gamma \cdot \cos|\alpha_s - \alpha| \qquad 2.9$$

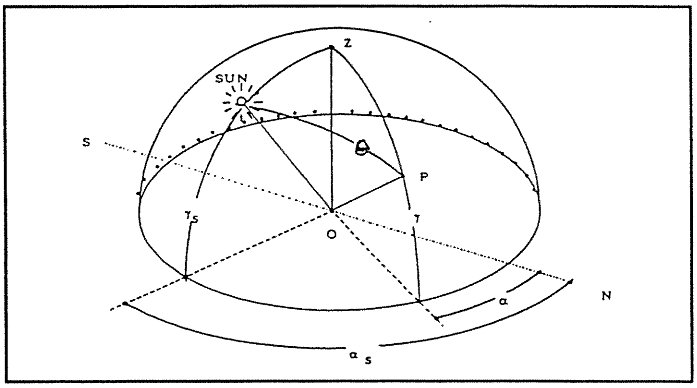


Figure 2.4 Angle nomenclature for the positions of the sun and sky element P [reprinted from CIE 1994].

2.3.3 Luminous efficacy of exterior illuminance

The radiation received on earth after traversing the atmosphere can be converted to daylight when the luminous efficacy of the radiation is known. Luminous efficacy of a light source is defined as the ratio of the total luminous flux (lumens) emitted to the total radiant power (watts) consumed [Littlefair 1985]. For an exterior, horizontal, unobstructed surface in Denmark, the total solar radiation normally received from a clear diffuse sky is 25-150 W/m^2, an overcast sky 25-250 W/m^2, while the direct solar radiation varies from 200-900 W/m^2. The average efficacies for the direct sun, the overcast sky and the clear sky affected by the atmospheric scattering and absorption, solar altitude, cloud cover and water vapour have been measured by Petersen for various sky conditions in Denmark [Petersen 1982]:

- Direct sun K_D = 103 lm/W (± 13 lm/W)
- Overcast sky K_{oc} = 121 lm/W (± 7 lm/W)
- Clear sky K_{cl} = 146 lm/W (± 14 lm/W)

The total solar radiation received on an exterior horizontal unobstructed surface can be derived from a weather data file such as the Danish Test Reference Year (TRY). The solar radiation data are converted to illuminances by the predicted, average efficacies for the direct sun, the overcast sky and the clear sky. Figure 2.5 and Figure 2.6 show the cumulative frequencies of daylight, *without* and *with* direct sun, respectively, received on an exterior horizontal surface for different occupancy periods. A certain point of the curve expresses the percentage of the actual occupancy period in which the exterior, horizontal illuminance is lower than the corresponding value on the abscissa. Figure 2.5 shows, for example, that, for an occupancy period from 08.00-17.00 hours, the exterior, horizontal illuminance *without* direct sun is expected to be in the interval 0-10.000 lux approximately 40% of the period and to exceed 10.000 lux approximately 60% of the period. This means, for example, that the interior illuminance at a reference point with a daylight factor of 2% will in the same occupancy period exceed an illuminance level of 200 lux during 60% of the period. A rule-of-thumb for daylighting design is represented by generally acceptable penetration of daylight providing the interior with a daylight factor of 2% at a distance from the window 2-3 times the height of the opening above the work plane.

Figure 2.6 shows the cumulative frequencies of daylight, *with* direct sun, received on the exterior, horizontal surface for the same occupancy periods. When taking the direct solar radiation into account, the illuminance level of 10.000 lux is exceeded during approximately 67% of the occupancy period.

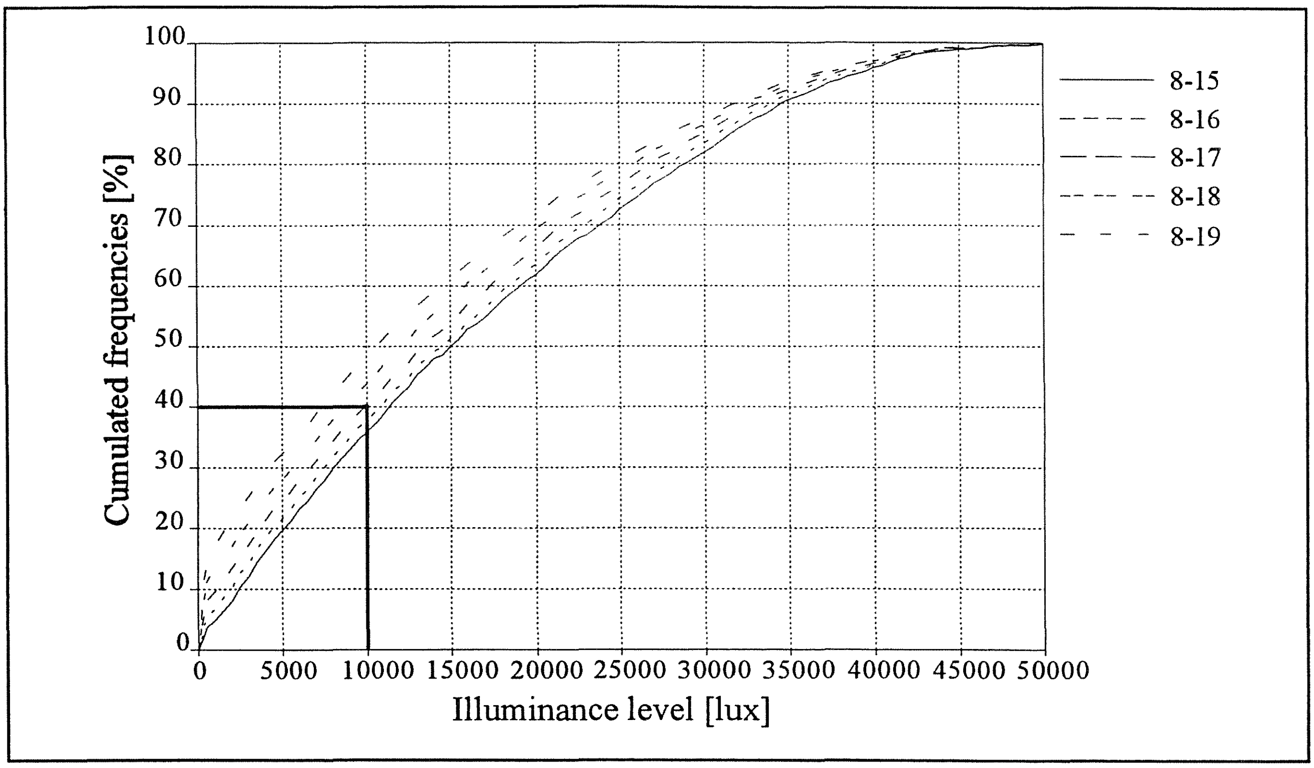


Figure 2.5 Cumulative frequencies in percent of selected occupancy periods of daylight on an exterior horizontal surface in Denmark (direct sun is excluded).

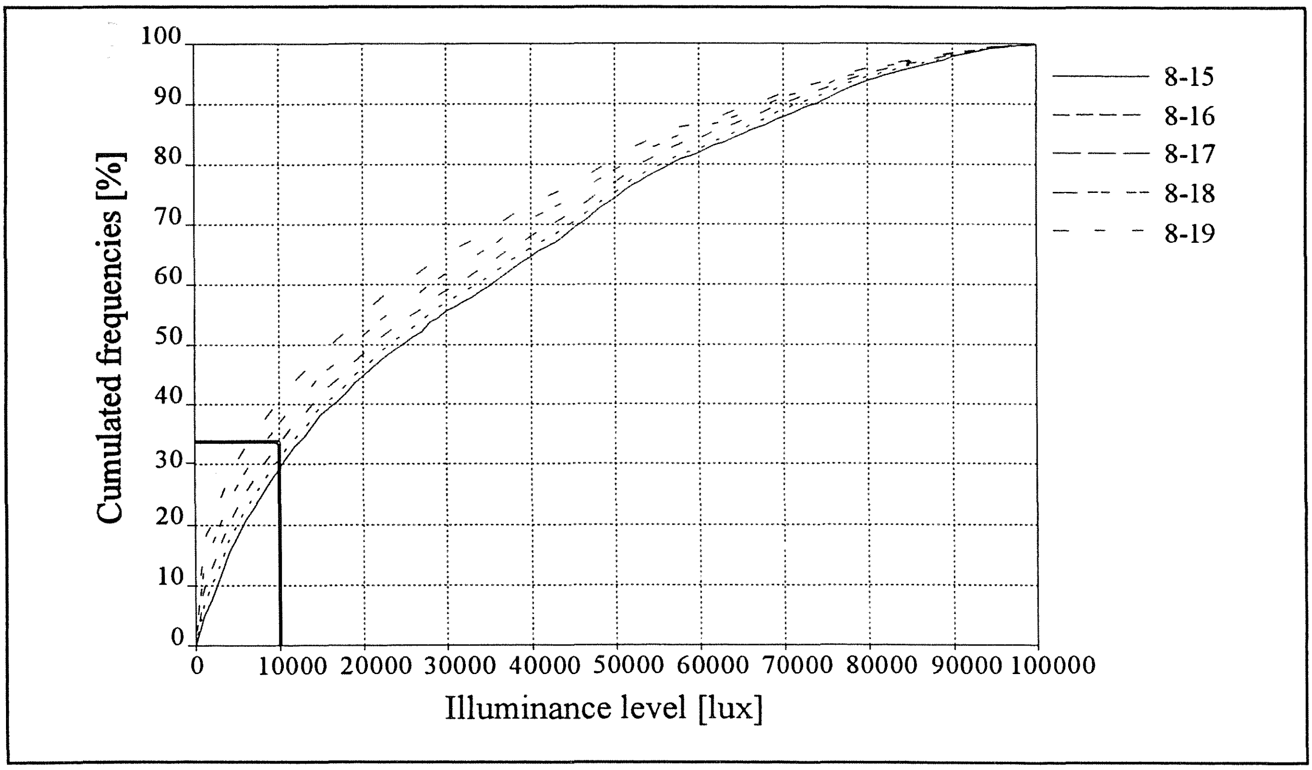


Figure 2.6 Cumulative frequencies in percent of selected occupancy periods of daylight on an exterior horizontal surface in Denmark (direct sun is included).

3. Daylighting Techniques

The main functions of windows are to fulfil human physical needs and psychological desires for windows, simultaneously admitting solar radiation and ventilation. A sidelighting window in the facade provides the interior with a flow of light from the side, resulting in a non-uniform luminance distribution where the window area is "too bright" and the area at the back may appear "gloomy". Different, innovative daylighting techniques intend to increase daylight availability in building interiors, improve uniform daylight distribution and reduce the need for artificial lighting. Many of these systems are developed in regions where sunlight plays a decisive role, and consequently they are inappropriate in climates dominated by cloudy conditions like Denmark. The main criteria for use of daylight systems in non-domestic buildings under cloudy conditions are that they must not block or reject diffuse skylight, but be movable, dynamic and cope with the sun's movement, when needed. This chapter describes and discusses integration of different daylighting techniques in the window envelope.

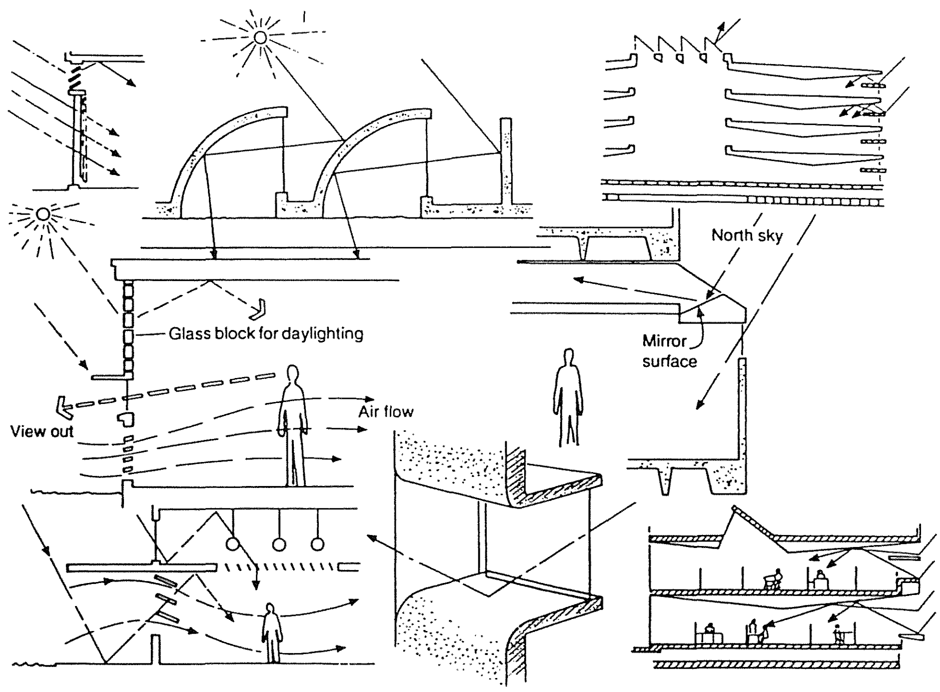


Figure 3.1 Illustration of different new and classical daylighting strategies in buildings [reprinted from Hastings 1994].

3.1 Brief history and trends of classical daylighting design

Daylight has become a major interest in the last decade because of its aesthetic possibilities and its ability to satisfy human, biological and global, ecological needs. Interior light in buildings is supplied by daylight and electric light, serving different interior functions and each reducing the deficiencies of the other. Emphasising environmental and global issues, intelligent use of natural light and artificial lighting control strategies will contribute to energy efficient buildings and reduce combustion of fossil fuels.

The invention of glass changed the function and characteristics of buildings. The art of producing glass was known in Egypt around 3500 B.C. and probably, even before, in the old Asian culture. Ancient Greeks used the sun to heat their homes, but the free openings reduced the heat gain in the winter.

Such problems were solved, as many other significant technological achievements, by the Romans who used glass (50 A. D.) and explored the thermal benefits of glazing their buildings [Fredningsstyrelsen 1977]. Glass and windows enabled to some extent, isolation of the interior from the external climate, exhibiting great significance for cooler climates in northern Europe. The intention of the window derives from the word "wind eye" (both in English and Danish), to ventilate (smoke) but also illuminate the interior by natural light [Baker 1993]. Ventilation of the interior was also associated with air quality problems and health problems by spread of diseases such as the plague.

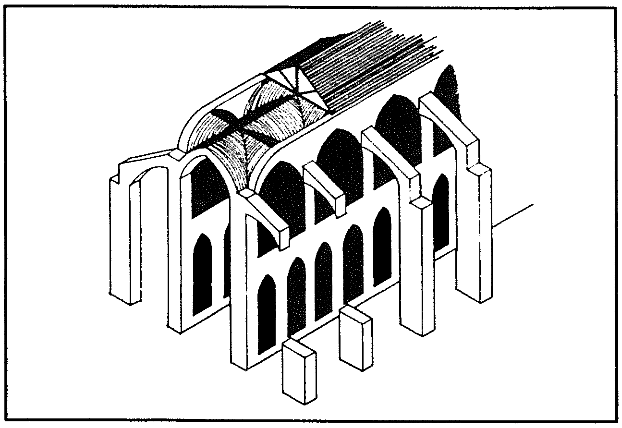


Figure 3.2 Groin vaulting and flying buttresses in Gothic cathedrals [reprinted from Lechner 1991].

Daylight design in architecture has always been important because it symbolises cultural traditions and human needs: "*We were born of light. The seasons are felt through light. We only know the world as it is evoked by light...To me natural light is the only light, because it has mood - it provides a ground of common agreement for man - it puts us in touch with the eternal. Natural light is the only light that makes architecture*" Louis I. Kahn [from Lechner 1991]. Glass was used in medieval ecclesiastical architecture, and made its earliest influence in sacred buildings, although the load bearing wall limited the width of the openings. Flying buttresses in Gothic cathedrals presented a skeleton construction, escalating larger windows in sacred architectural design (Figure 3.2). During the Industrial Revolution (19th century) architectural design changed, because the rural population moved to the cities to work in mills and factories, and changing working conditions to indoors introduced the need for natural light. There had been advances in the production of artificial light, such as the incandescent gas mantle invented by Welsbach in 1885, but the quality and luminous efficacy of the light source were low and expensive to use, compared to daylight. With the culmination of post and lintel construction (19th century), skeleton construction produced daylight buildings with large and numerous windows: "*Designers have achieved increasingly larger window openings, and eventually the all glass wall, in order to enhance the visual quality of the building interior by means of daylight*" Le Corbusier [from Button 1993]. By enhancing the development of a skeletal framing, first of cast iron, then wrought iron, and later steel and reinforced concrete (20th century), a whole new architectural design for the use of natural light and ventilation was born. Glass buildings, such as the Crystal Palace in 1851, became a possibility because of the increased availability of glass, combined with the use of steel structures. Also new techniques in glass production and framing technology were invented, reducing cost and increasing the area of the glass panes. Together, glass and steel skeletons became a key element in the modern architectural movement. The architectural movement's ideals were concerned with natural light, transparency, health and social well-being and they saw that glass would provide and symbolise these ideals.

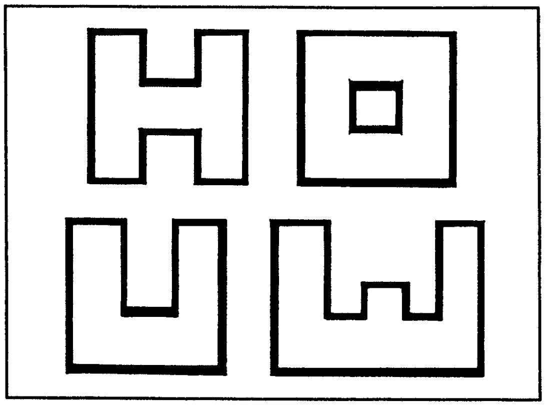


Figure 3.3 Common floor plans of multi-storey buildings prior to the 20th century [reprinted from Lechner 1991].

The requirements of daylight and ventilation became an essential aspect of the architecture, taking the ideas from the Renaissance architecture, by its E- and H-shaped floor plans (Figure 3.3). The room depths in these multi-storey buildings were often limited to about twice the floor to ceiling height in order to permit adequate penetration of natural light [Baker 1993]. Natural light in deep floor-plan multi-storey buildings was solved by piercing sections with light wells (or atria). Until the second half of the 20th century, when (some say) fluorescent lighting and cheap electricity became available, daylight and architecture were interpreted as being the same. At the beginning of the 20th century, daylight was still the main source of light during daytime, using artificial lighting at night.

However, the developments of fluorescent lighting in the 1930s changed the use of daylight as a design criterion, due to the drastic increase in artificial lighting efficacy and mechanical ventilation, resulting in a reduced need for windows, natural light and ventilation. Heat loss through the thermal envelope was reduced through the technological development in building materials and constructions, although single glazed windows were still common in the 1950s and 60s. The energy crisis in the mid-1970s reexamined the potential for natural light in buildings, since the glazing unit was sometimes addressed as the main source of heat loss and undesirable solar gain. To reduce solar gain and heat loss, the clear glass was sometimes replaced by tinted or reflective glass and the exterior environment excluded from the interior by decreasing the glazed area. Reduced natural light in the interior increased the daytime needs for artificial lighting, presenting new design problems. Banham (1969) defined these problems as: "*For the first time it was possible to conceive buildings whose true nature could only be perceived after dark, when artificial light blazed out through their structure. And this possibility was realized and exploited without the support of any corpus of theory adapted to the new circumstances, or even of workable vocabulary for describing these visual effects and their environmental consequences. No doubt this accounts for the numerous failures of this century to produce the effects and environments desired; equally doubtless it accounts for periodic waves of revulsion against "glass boxes" and fashionable returns to solid concrete and massive masonry* [from Button 1993]."

The Danish Government presented in December 1988, a plan of action on the environment [Danish Ministry of Energy 1990]. The plan aimed at considerable reductions in the energy demand and more intensive use of natural gas and renewable energy. These recommendations were based on the report by the World Commission on Environment, the Brundtland Report, and the United Nations' Environmental Perspective to the year 2000. To accomplish the objectives of the Danish energy plan, enhanced use of natural light is promoted with the new Danish Building Code 1995 [Danish Ministry of Housing 1995], by increasing the window area from 15% to 22% of the floor area. Therefore, realistic reduction in energy consumption will emphasise the importance of daylight used as an integrated and adopted part, not only with electric lighting, but also with the window system as part of the building envelope. The building design must therefore be coordinated to produce an efficient and aesthetically satisfying interior, without ignoring other aspects of the environment affecting human comfort.

3.2 Classical sidelighting design

The purposes of a classical sidelighting design are to provide: - interrelationship between the exterior and the interior, - adequate, interior natural light levels, - natural ventilation, - view to the outside, - acoustic interchange, - protection from the exterior climate the whole year. The main deficiencies with traditional sidelighting systems are that they tend to contribute to bright luminance areas in the window perimeter zone and dim areas at the back of the room. Use of daylight also challenges the building design, not only by its variability in intensity and direction, but also the complexity of heat and light transfer through the fenestration. The interior receives exterior light from the sun, the sky and by reflection from the ground and other surroundings (buildings, plants etc.), causing interior variability in the direction of natural light.

General "rules-of-thumb" for window design are almost impossible to define and justify, because of numerous variations in external conditions, building use, orientation and human needs, etc. Some evidence implies that both visual and thermal satisfaction can be achieved by a window area of approximately 20-30% of the floor area. Adequate interior illuminance levels depend upon the width and height of the window above the work plane, the glazing material used and control elements applied. The penetration of daylight is generally acceptable at a distance from the window 2-3 times the height of the opening above the work plane (a daylight factor of 2%). Increased window height will provide deeper, interior daylight penetration, but also increased exposure to sky and sun with the brightest luminances, increasing the potential level of glare and the need for control elements. The benefits are, besides higher illuminance levels, an exterior view of greater depth, both in the foreground and further away. Dividing the window area into several windows of an equivalent size, reduces glare problems and produces a more uniform distribution of light, but this impedes the exterior view. Horizontally shaped windows will reduce glare problems and interior illuminances while providing a panoramic view outside.

Glazing types

The design of the building envelope for a climate like that in Denmark is a balance of the need for solar control to reduce the risk of overheating, against the need for high levels of natural illuminance and the benefit of passive solar heating. Glazing materials vary in their light and heat transmitting characteristics depending on optical properties of the material, e.g. the reflectance and absorbtance mechanisms of the glazing. The aim for high utilisation of natural light in the interior leads to the use of glazing admitting the maximum amount of visible light, while reducing the ultraviolet and infrared portions in the spectrum. No glazing materials transmit 100% of visible solar radiation, because a fraction of the radiation is absorbed depending on glass additives and glass thickness, while another fraction is reflected depending on the glass surface and the angle of incidence of the radiation. Light transmitted through the glass is subject to modifications by refraction, diffusion and colouring. Several glass types have special characteristics of light and solar transmission, changed by the glass composition or by a surface coating. Also, the amount of transmitted solar radiation is a function of the angle of incidence and the glazing material itself. The transmittance is almost constant for solar radiation striking the glass at angles between 0 and 50°, while above 70° the reduction is pronounced since the light is reflected instead of being transmitted.

A typical window pane contains two layers of clear float glass of the soda-lime-silica type, generally composed of 70-74% silica (SiO_2), 5-12% lime (CaO) and 12-16% soda (Na_2O), with small amounts of magnesium, aluminium, iron and other elements. The iron oxides create a greenish tint because of the impurities in the sand together with aluminium. The thickness of a float glass pane varies from 2 mm to over 25 mm with a typical glass thickness of 4 mm to 6 mm in a double glazed unit with a space between glass panes of 6-12 mm. To enhance the thermal insulation, the gap is often filled with argon or krypton instead of air [Scanglas 1986, Aschehoug 1991, Burton 1993].

Reduction of solar transmission may be provided by windows with body tinted glass. This is produced by small additions of metal oxides, which affect the thermal and optical properties of the glazing by reducing the transmittance of solar radiation. The metal oxides used are iron, cobalt, selenium together with a range of colour shades, either grey, green, bronze or blue [Shuman 1992 b,d]. The intention of tinted glass is to reduce the transmission of specific wavelengths of light, mainly the infrared spectrum, while minimising the alteration of light transmission in the visible region. In the visible spectrum, blue and green colour shades will transmit a higher fraction of visible light than grey and bronze. In a double glazed unit, tinted glass is positioned as the outer pane so that the heat is more easily dissipated to the outside. Solar transmission can also be reduced by increased reflection of incident radiation by adding a reflective metallic coating. However, the use of tinted or reflective coated glazing as a daylight and passive solar promoting element will seldom be appropriate in Denmark, since such systems filter and reduce light and block desirable winter sun as well as altering the colour of the outside view. Some positive aspects are that they may exclude the needs for shading devices, reduce the interior glare problems and increase thermal comfort by reducing undesirable summer sun.

The low-E glazing refers to application of low emissivity coatings on the clear glass pane with a thin metal layer of gold, silver or copper, combined between layers of tin oxide to increase adhesion and reduce corrosion [Burton 1993]. Low emissivity coatings is more translucent to short wave radiation, without substantially altering the transmission of visible light. Low-E glazing in the window will increase the temperature of the inner glass surface and decrease the effect of colder, long wave radiation associated with emissivity and reflectance in the far infrared region [Aschehoug 1991]. Sealed low-E double-glazed units may also contain gases with lower thermal conductivity than air such as argon, providing further improvement of the U-value. "Futurology" is a selective coating, sometimes called cool-daylighting, with the intention of rejecting the infrared heat radiation without reducing the visible transmission [Aschehough 1991, Shuman 1992 b,d].

Clerestories
The clerestory strategy, first introduced in sacred buildings, combines toplight and sidelight strategies to provide light in large interior spaces (toplighting) [Hastings 1994]. In sacred buildings, clerestory windows parallel to the primary axis produce special lighting effects, as a consequence of the development of flying buttresses providing a skeleton construction. Today, clear clerestory windows are mainly used as a toplighting strategy in wide, low-rise buildings, such as convention centres, sports arenas, and other large open spaces, to increase the interior light level. As a sidelighting strategy, the clerestory is attached above the vertical view window as a daylight window (see Figure 3.4). This increases the window area in a sidelit office combined with an innovative sidelighting system, such as light shelves, prismatic panels, fixed reflective louvers etc. The innovative system can either be attached to the clerestory window or in between the glazing to reduce maintenance.

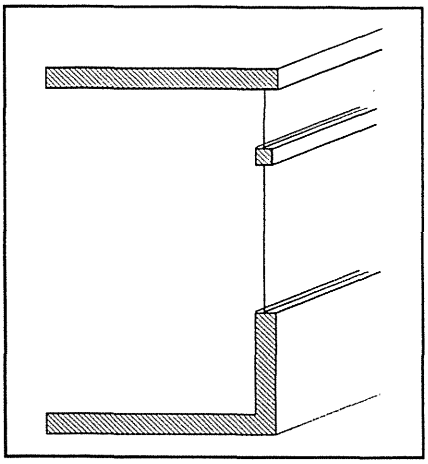


Figure 3.4 Clerestory window used in a sidelighting system.

Light shelves
The use of light shelves is a classical side lighting technique, known by the Egyptian Pharaohs, mainly to control sunlight, and later to reduce glare and improve the interior illuminance levels [Lam 1986]. The system is a horizontal, or a nearly horizontal baffle, situated in the window facade, either inside, outside or combined, dividing the glazing and function (see Figure 3.5). Light shelves are designed to shade and reduce illumination from sunlight and diffuse skylight near the window, and redistribute the shaded part of light deeper inside the building core. However, the redistribution efficiency can be reduced since the internal shelf acts as a dust collecter while the external shelf (sometimes self-cleaning) becomes a dirt and snow collector and/or a nesting place for birds or insects.

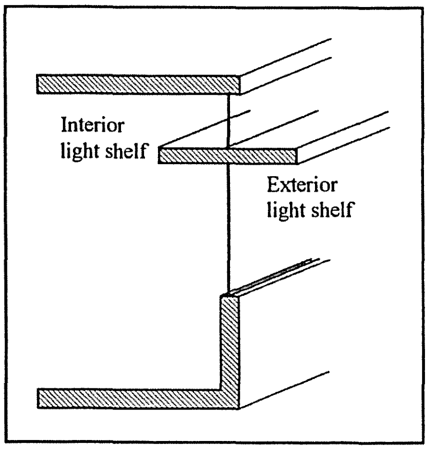


Figure 3.5 Combined interior and exterior light shelf.

The intentions of the light shelf are to "increase" the illuminance level at the back of the room and reduce the need for artificial lighting and thereby the total energy consumption. However, measurements for diffuse skylight alone (overcast) show that windows with light shelves produce an overall reduced work plane illuminance level, compared to an unshaded window of equal size [Aizlewood 1993, Lam 1986, Shuman 1992a, Selkowitz 1983, Benton 1986, Baker 1993, BHKRA 1985]. Measurements at the Building Research Establishment (BRE) were conducted in two identical south-facing mock offices with an internal shelf 1 metre deep at 2.08 m above floor level [Aizlewood 1993]. The upper surface of the light shelf had a matt white and reflective finish, respectively. Results show for an overcast sky, reduced light levels by 5-30%, highest in the intermediate zone while lowest reduction at the back of the room. For a clear sky, the reduction is less (0 to 20%), although areas near the window are shaded. Changes in the sun elevations and the profile angles affect the areas where reflected light from the shelf strikes the surfaces of the room. Measurements of an interior and exterior are discussed in chapter 6.

"Optimal" designing of a light shelf depends on the height, depth, shading requirement, location and size of the clerestory window, surface reflectance and material property, slope and construction methods. A light shelf is usually positioned 1.9-2.1 m above floor level, dictated by the room configuration (ceiling height) and eye level of a standing person, to avoid reflected glare. A lower position will increase the amount of light reflected to the ceiling, but will increase visual distraction in the interior often to an unacceptable level. Visual discomfort can be reduced if the light shelf reduces the brightness of the window area and modifies the contrast between the darkest and brightest part of the room. This will again depend on the light shelf's geometry, material properties and position to reduce the exposure of visible sky and its ability to increase interior adaptation luminance. A light shelf can reduce window glare since adjacent surfaces, such as the ceiling and upper part of the side walls, receive more light.

A light shelf cannot shade the interior all year round because of the low elevation of the sun during winter (Figure 3.6). Increased depth reduces the problem but also obstructs the desired daylight penetration and outside view. Shading the window perimeter by tilting the exterior light shelf downwards reduces light reflected to the ceiling. Upward tilting improves daylight penetration of reflected light, but reduces the shading effect of the window perimeter. Therefore, a horizontal light shelf provides the best compromise with a ratio between the depth of the shelf and clerestory window height of 1 to 1.5.

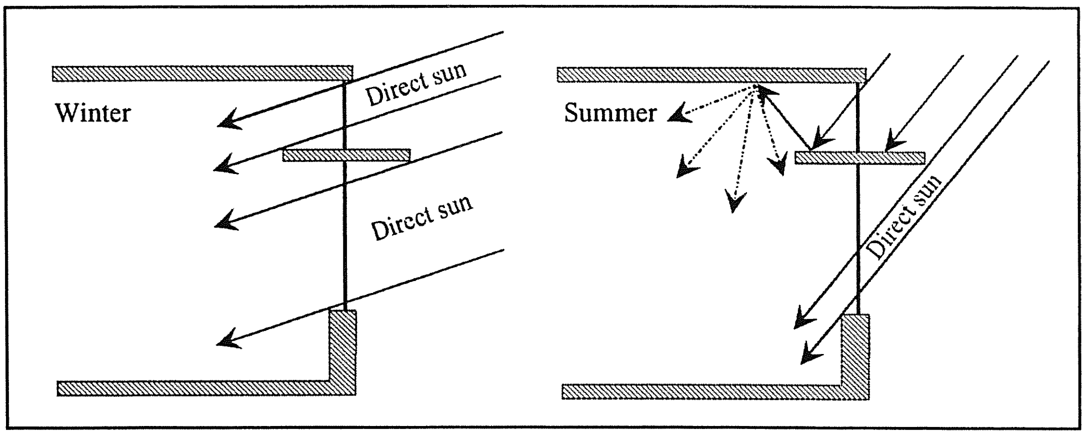


Figure 3.6 Penetration of direct sun for low (winter) and high (summer) solar altitudes for a light shelf in Denmark.

The finish of the light shelf influences the "efficiency" and direction of light redirected from the upper surface to the interior. A matt finish produces diffuse reflection with no directional control, contrary to a specular reflection where the angle of incidence is (almost) equal to the angle of reflection. An ideal matt, Lambertian, diffuse surface reflects light equally in all directions. A highly reflective surface (a mirror, aluminium or a polished material) produces more light to the ceiling than a diffuse surface, but needs a higher maintenance to maintain the reflective properties. Lam points out that "*Perfectly polished mirrors must be very flat and uniformly clean or dirty to avoid distracting, distorted patterns on the ceiling*" [Lam 1982]. But a reflective surface can introduce glare problems and visual distraction in the interior, either by itself, or by a bright light band at the ceiling and sidewalls with "extreme" luminances (30.000 cd/m^2). In most circumstances, these high luminance areas should be avoided, especially in the line of sight. For a matt, diffuse surface (Lambertian), only half of the reflected light will be distributed into the room, but for an interior light shelf, some of the "lost" light is reflected towards the interior from the clerestory glass surface.

A more sophisticated type of "light shelf" has been developed by Compagnon, by use of non-imaging optics to design the shape of reflectors [Compagnon 1993 & 1994]. The system, a so-called anidolic concentrator, is attached, between the glazing, to the clerestory window as an exterior collector of the high luminance area near the zenith, combined with two interior non-imaging reflectors (see Figure 3.7). The anidolic daylighting system transmits light rays from the half-hemisphere faced by the facade. Simulation and analysis with ray-tracing techniques show a high light transfer efficiency, due to little inter-reflections of incoming rays. Compared to a traditional light shelf, the anidolic system creates a better illuminance uniformity, by an increased illuminance level at the back of the room, and simultaneously acts as a shading device for the perimeter zone near the window.

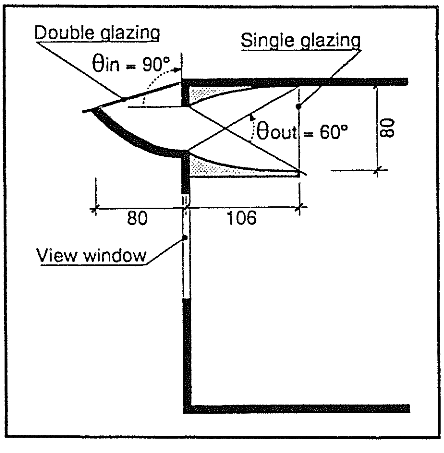


Figure 3.7 Section of an anidolic daylighting system [reprinted from Compagnon 1993].

Sill

The sill strategy is often an exterior, horizontal or downward tilted surface situated below the window opening (Figure 3.8). A sill reflects and redirects light striking the surface to increase interior light levels determined by size, tilt and surface finish [Baker 1993]. The size of the sill often corresponds to the recessed distance of the window glass from the external surface of the wall, using diffusive light-coloured concrete or bricks as the main construction material. Other materials such as a mirror, aluminium, highly polished surface or glossy paint will increase the directional reflected light and contribute to disturbing reflected glare as a result of the sill's position below eye level. Tilting the surface downward and away from the window will reduce reflected glare and increase the amount of ground-reflected light. The sill strategy is only recommended for north-facing windows or windows facing high obstructions (such as in narrow streets) or in climates where overcast sky is the main source of daylight. Extending the concept further as an exterior "light scoop", collecting a larger portion of zenithal luminances, will boost the amount of daylight and direct light into the interior. This technique is more appropriate as a side-lighting system for rooms facing the interior of an atrium, but caution regarding reflected glare is necessary.

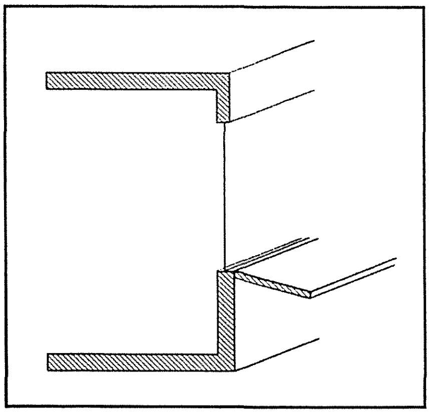


Figure 3.8 Downward sloped exterior sill.

3.3 Classical shading systems

Any non-domestic building design in Denmark introduces the need for protection against solar radiation entering the interior. Shading windows will therefore always be a balance between the desire for high passive utilisation of solar heat and daylight and a pleasant view and the need for reduction of solar loads in summertime. Fixed shading devices can be crucial to a building design designated to use daylight, in climates dominated by cloudy conditions as in Denmark, while movable shading devices are more flexible and dynamic. The total solar load on the building consists of three components: direct, diffuse, and reflected radiation. Control of direct solar radiation dominates the design, but the solar radiation from diffuse skylight and reflected light can also be significant. External shading devices are preferable, to control excessive passive solar heat gain by direct solar radiation and to prevent glare. However, internal or window-integrated systems are usually sufficient to cope with diffuse skylight due to the large exposure angle from diffuse radiation. The reflected component is controlled by reducing the reflectivity of the exterior surfaces, e.g. the use of plants.

To prevent passive solar heating entering the building, the shading device must be "in phase" with the external thermal conditions and shade during overheated periods (summer) and allow solar gain during the heating season. An "optimal" shading system in Denmark should therefore be movable, dynamic and cope with the sun's movement and not reduce diffuse skylight when there is a heating demand. Such strategies have been emphasised by Frank Lloyd Wright as *"these newly freed exterior walls can be treated as "screens," to shade where the sun is too strong, or to bring sunlight when warmth is welcome, and shelter the interior from any adverse weather conditions, and yet allow natural light to fill the space"* [IDC 1986].

The southerly orientated window allows high solar energy gains during both winter and summer, necessitating a fixed or a movable shading device to reduce the unwanted solar energy gain. An east/west facing window provides, to some extent, extreme conditions which are difficult to control: light and heat gains through the window due to low solar angles, necessitating a movable shading device. The northerly orientated window provides low energy gains and interior illuminace levels, due to the almost complete absence of direct sun. The most commonly fitted external shading devices in Denmark are variations of either the horizontal overhang, the vertical fin or a combination of both. The design of fixed shading devices is determined by the sun and profile angles, orientation and latitude, as well as the external, thermal conditions. A movable shading system, such as an awning, rotating horizontal or vertical louver or roller shade can be either simple or complex, automatically or manually adjusted daily or according to a predefined time sequence depending on sun angle and thermal conditions.

Overhangs

An overhang is usually a horizontal feature extending from the facade above the window (Figure 3.9). Historically, the overhang strategy was widely used in dwellings to extend the pitched roof. The overhang exterior depth is normally designed to protect the window perimeter zone as a seasonal shading (summer) and glare control device. The horizontal overhang usually extends 0.4 to 1 m from the facade, providing shade without redirection of sunlight, but utilises diffuse and ground-reflected light depending on size. Southerly orientated overhangs shade direct solar radiation and reduce the passive solar heat gain in the summer. The shading effect is reduced for an east/west orientated overhang due to low morning and evening sun elevations. Low sun angles can be shaded by a downward sloped overhang of reasonable size or by a movable shading device.

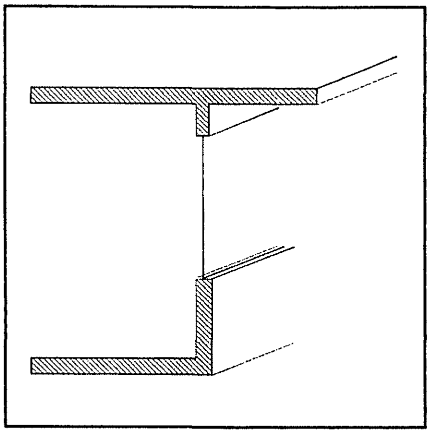


Figure 3.9 Overhang shading the window for direct sun.

Sidefins

Sidefins are vertical shading devices extending from the exterior facade (see Figure 3.10) controlling the low sun angle for the east/west facing window. Combination with a horizontal device (overhang) will provide a simple and effective shading system. A sidefin tends to frame the panoramic exterior view and enhance the vertical view of the sky dome. Inward sloped fin angles shade the interior more effectively but increase dissatisfaction with the exterior view. Outward sloped fin angles enhance horizontal view and reduce shading efficiency. Natural light falls laterally on sidefins, reducing the reflected and redirected light to adjacent sidewalls in the interior. Downward reflected sunlight from specular vertical surfaces produces potential glare angles, so the use of diffusive finishes is recommendable. Sidefins will not reduce window glare from bright sky luminance or from the constant change in brightness of the external vertical surfaces. The geometry of the sidefin is usually determined by window height whilst the exterior depth varies between 0.3 to 1 m. The exterior depth of a sidefin, in all four compass directions, may affect interior thermal conditions by reducing direct solar radiation and passive solar gain. Southerly orientated fins shade low angle sun received at the beginning and the end of a day, while easterly and westerly orientated fins shade high angle sun around noon. North-facing sidefins reject direct early morning and late afternoon sunlight in midsummer, and should only be considered in special cases.

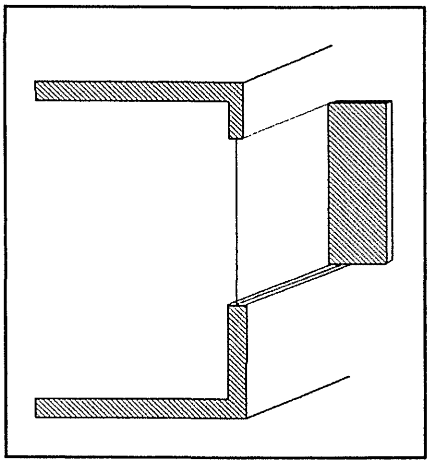


Figure 3.10 Side fin shading the window for direct sun.

Awnings

An awning is a movable, exterior canvas with a similar shading effect as the overhang but different due to its movability, weight, maintenance, durability and colour fading (Figure 3.11). The canvas is opaque or diffuse (several colours) shading direct solar radiation and reflecting groundlight to the interior by a light-coloured inner surface, minimising the contrast with the outdoor scene. Movable awnings can cope with solar radiation by blocking or filtering (diffusive) direct solar radiation or maximising admittance of diffuse skylight (overcast) when raised. Adjusted awnings can prevent direct sun and overheating (summer), admit passive solar gain (winter) and prevent glare from direct sunlight and diffuse skylight. Translucent awnings admit more light and improve the outside view, compared to the solid overhang, but at certain incidence angles (morning and evening) sunlight will penetrate inside through the side openings, if these are not shaded.

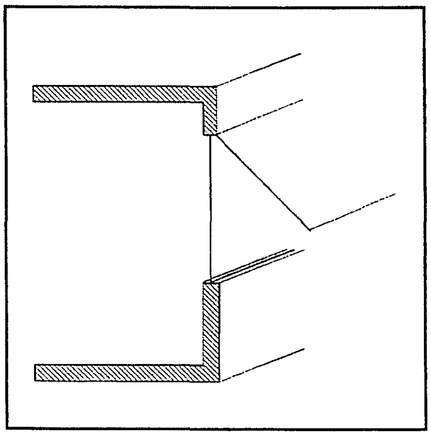


Figure 3.11 Awning shading the window for direct sun.

Curtains
In most non-domestic buildings, curtains are the traditional window shading "system", because they allow for personal taste and variation besides partly or totally blocking direct sun and diffuse skylight. Interior curtains or curtains between glazing are often used in the "view window", as the controlling element most likely to be adjusted by the occupants when needed. They are made of translucent material allowing transmitted, diffusive light and privacy inside, or opaque material for total privacy and to block daylight, so as to darken the interior, or as an insulating material. This shading device is flexible and easy to remove and open up the interior for solar radiation and the view when required, either by rolling them up or drawing them aside.

3.4 Classical toplighting design

Toplight strategies are seldom used in multi-storey, non-domestic buildings, because they illuminate only one or two interior floor levels and tend to produce visual dissatisfaction due to glare and lack of view. Their applicability is therefore only described briefly by its qualitative and quantitative aspects to illustrate their use and consequences (Figure 3.12). Low-rise toplit buildings (industrial premises, malls, etc.) with limited glazing area may provide the interior with an efficient, uniform and flexible (if desired) illuminance level. In non-domestic buildings, toplighting should only be used to supplement the interior with natural light and not to replace the sidelighting system. The toplight systems described, introduce potential glare problems, either from direct sunlight striking the occupants, by veiling reflection in the offending zone or as a source of glare itself.

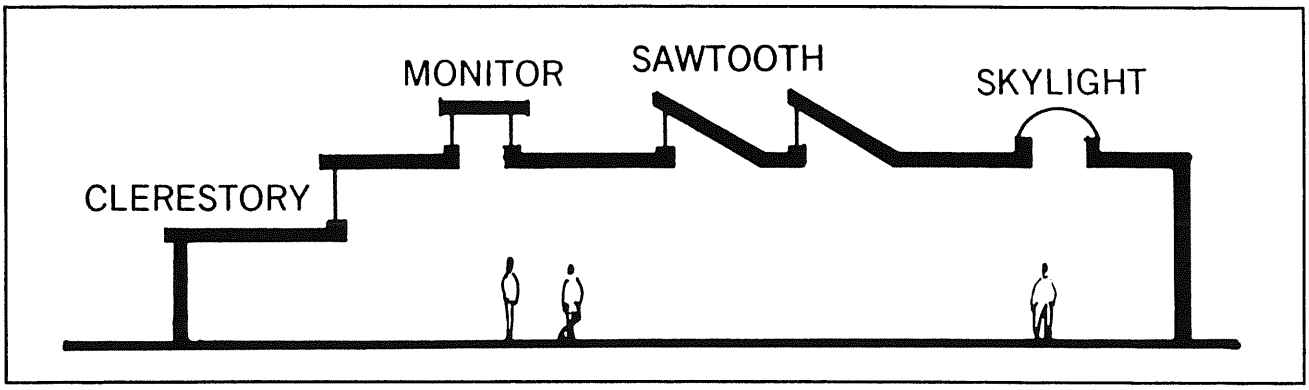


Figure 3.12 Different toplighting systems and possibilities of daylighting the interior [reprinted from Lechner 1993].

Skylights
Skylights are horizontal or slightly sloped openings in the ceiling surface (see Figure 3.12). The system often provides uniform, interior illuminance levels, because the skylight's solid angle to the unobstructed sky is "optimal" for collecting and distributing high zenithal luminance from the diffuse sky (clear sky and overcast). Skylights can be located almost anywhere in the ceiling construction with minimal impact on the roof structure. The thermal energy performance of the skylight is unfortunately reversed, since it admits maximum solar radiation in the summer and minimal heating loads in the winter. Skylights also give the maximum unobstructed view of the sky, thus increasing the exposure to direct glare and sunlight problems in the interior. Diffusive, translucent skylights tend to be excessivly bright on clear days causing interior glare problems. Increasing the depth of the ceiling opening (light well) combined with interior baffles will increase light reflected to the interior and reduce glare. Despite the advantage with skylights, they may reduce information about time and weather conditions if not designed correctly. The geometry and sidewall reflection properties will influence the distribution and penetration of light at the work plane, but may leave the sidewalls and the ceiling unlit and gloomy. Reflecting light to the ceiling and side walls with interior baffles or heliostat-mounted reflectors [Caddet 1992] could overcome these deficiencies for the unlit interior surfaces.

Sawtooth and monitors
A sawtooth toplighting strategy, with a vertical or steeply sloped clerestory glazing (see Figure 3.12), admits daylight to the interior of one-storey buildings similar to a vertical side lighting window. The

main difference between sawtooth and monitors is that monitors allow penetration of light simultaneously from two or more directions. A south-facing sawtooth admits more low elevation sunlight in the winter than summer, and thereby copes better with the needs for solar gain in winter. A north-facing sawtooth will produce a low constant daylight distribution and reduce problems with glare, while east and west orientated sawtooths should be avoided. One consequence of vertical or sloped toplighting systems is a reduced view to the sky and thereby less natural light to the interior compared with skylights. Typical shading strategies for the sawtooth construction against glare problems and veiling reflections are exterior overhangs, translucent glazing, internal baffles etc.

3.5 New daylighting strategies

The "flow" of daylight in buildings is both difficult to handle and a technical challenge, since the design will always be a compromise between the heat loss and the solar heat gain, interior light, the view outside or inside and the architectural appearance of the window and facade, etc. The aim of daylight design in Danish non-domestic buildings should emphasise either control of direct sunlight or "improved" penetration of diffuse skylight. Some existing technologies transmit direct sunlight to the interior by collecting, focusing and concentrating while diffuse skylight is transmitted by redirection in more beam-like projected distribution.

3.5.1 Innovative glazings

During the last decade, research and development in the glazing technology have been focused in two directions: superinsulating glazing (vacuum, aerogel) and glazing which can be controlled (switchable glazings). The selection of glass type will influence the interior building design by its total transmittance and spectral and optical properties. The interior thermal and visual comfort depends on the dynamic response of the glazing's ability to cope with the variation of external thermal conditions by selective control of one or more of the glazing properties. Each glazing system will produce new possibilities in the design of a traditional window, because solar heat gain and heat loss are reduced without extensive alteration of the transmission of visible light. This may again improve the potentials for the use of natural light inside.

Superinsulating glazings

The effort regarding developments of a superinsulating glazing type is driven by the substantial heat loss through the window envelope. In cold climates, like in Denmark, an improved U-value of the glazing unit and the frame will decrease these deficiencies without extensive reduction of daylight transmission. Superinsulating glazing may provide new architectural flexibility, especially regarding window area and enhancing the penetration of daylight into the interior. The multi-layer glazing unit with several low-E coatings, together with gas-filled cavities (argon, krypton and xenon) has a centre U-value below 1.0 $W/m^2 K$ [Hastings 1994]. A well-designed, multi-layer window causes more thermal energy gains than losses during a winter day. This may again expand the possibilities for increased use of natural light even for a north-facing window. However, cautious design is needed to secure the human needs for a satisfactory indoor environment without extensive, reduced transmittance of visible solar radiation or altered spectral colour transmittance.

Monolithic silica aerogel

Monolithic silica aerogel panels, sealed in a glass unit and evacuated, may reduce the centre U-value to approximately 0.4 $W/m^2 K$ (20 mm thickness). Aerogel is a chemical composition of almost 100% SiO_2 or quartz, with a density of 70-250 kg/m^3 and a thermal conductivity of 0.020 $Wm^{-1}K$ at room temperature and atmospheric pressure [Jensen 1991]. The disadvantage with aerogel is that it is easily damaged by water, has low tensile strength and the transmitted light is altered by refraction, diffusion and colouring. The normal solar transmittance for a 20 mm thick silica aerogel has been measured as 87% (no glazing) with a colour rendering index R_a of 95 [IEA 18 1995]. Subjective evaluations of the optical qualities viewed against a bright background, indicated that the colour of the view was reduced to slightly hazed and yellow, whilst it was slightly blue against a dark background [Jensen 1991].

Vacuum windows

A vacuum window is a traditional, but non-commercial product, an evacuated double glazed unit with one or two low-E coatings. The window has hermetically sealed edges and an array of support pillars to maintain separation under atmospheric pressure. By evacuating the space between the two panes, conduction and convection are essentially eliminated as well as the radiant heat transport due to the internal low-E coatings. Measurements suggest an improved centre U-value of approximately 0.6 W/m^2 K (one coating) and possibly as low as 0.4 W/m^2 K with two coatings (yet to be proved) [Bredsdorff 1992]. The vacuum window has an identical solar radiation transmittance, spectral and directional properties as a window with low-E coatings [Collins 1992].

Switchable glazings

Switchable glazings vary the optical response to the exterior condition in transmission of light and radiation. The dynamic, optical transmittance changes by a reversible automatic response to either light levels, temperature or an applied electrical signal.

- electrochromatic, where transmission is changed by applied current
- photochromatic, where transmission is changed by the amount of incident radiation
- thermochromatic, where transmission is changed with temperature

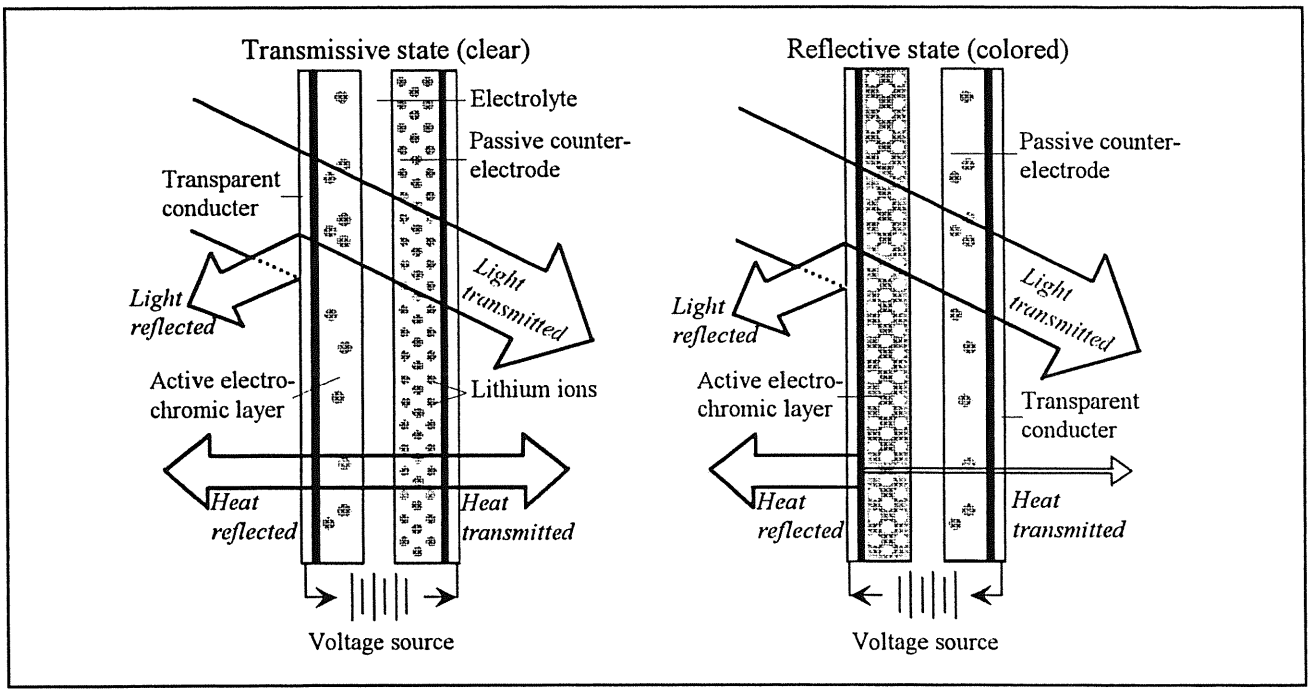


Figure 3.13 Principle illustration of the electrochromatic glazing [after Selkowitz 1994].

Electrochromatic glazing

An electrochromatic glazing consists of a multi-layer glazing unit combined with an active, thin, electrically controlled, liquid crystal film applied to the outer glass pane (or plastic substrate) and a passive counter electrode on the inner glass pane. The electrically controlled, liquid crystal film can be reversibly responsive from transparent to translucent. The electrochromatic coating is typically a complex, five-layer structure (Figure 3.13). Application of low-voltage current transfers lithium ions to the active electrochromatic layer and changes the glazing unit from clear to a dark-coloured condition (typically blue, grey or bronze). A reversible current returns the glazing to its clear state [Shuman 1992a-d, Selkowitz 1994]. Two electrochromatic prototypes exist with different thermal, spectral and optical properties: a broad-band and a narrow-band. The broad-band electrochromatic glazing transmits solar radiation in the clear state and absorbs in the dark-coloured state. The narrow-band electrochromic glazing also transmits solar radiation in the clear state, but in the dark-coloured state it reflects the visible radiation and maintains low transmittance and high reflectance in the infrared spectrum. The light transmission for the prototypes varies in a range from 6 to 60%.

Photochromatic glazing
Photochromatic glazing changes its reversible optic or colour transmittance of solar radiation as a function of incident light in the entire solar spectrum. The glazing usually absorbs a decisive part of incident visible radiation, thus reducing its beneficial concept in windows [Shuman 1992a-d]. The photochromatic process, known in sunglasses, is a reversible optical density change due to the chemical compound between the state of the energy triggered by electromagnetic radiation producing two unequal, spectral absorbing situations. At present, organic or inorganic photochromatic reversible materials exist, but are not commercially available products.

Thermochromatic glazing
Thermochromatic glazing uses a gel of organic polymers in between glass panes. This gel, a temperature dependent light transmittance (TALD), switches reversibly to an adjustable set-point temperature, from transparent to a diffuse, translucent condition. Light transmission measurements on a prototype, with a 10 mm gel in a multi-layer glazing, indicate that visible light transmission vary from 15 to 65%. The transmitted radiation for the translucent condition is almost totally diffusely scattered [IEA 12 1992, Shuman 1992a-d].

3.5.2 Innovative side lighting systems

Recent years have brought new daylighting concepts to the market. These new, innovative sidelighting systems may be situated on the outside, inside or in between glazing in the window envelope, or in a separate clerestory window. This "new" facade solution divides the window function into a daylight element and a viewing window for visual, exterior communication. An innovative system usually alters the natural behaviour and flow of daylight, thus changing the interior luminance distribution. The following overview of new daylighting systems relies on a similar overview in [Littlefair 1988 & 1990] and BRE's results of a full-scale experiment with "new" innovative daylight systems [Aizlewood 1993]. Most of the systems examined actually reduce or reject diffuse skylight since they are primarily developed to control and redirect sunlight. None of the innovative systems described are daylight collectors, and they will therefore provide less interior light than admitted by clear, unobstructed glass. However, innovative daylight systems merely redirect light from the window perimeter zone to the back of the room, thus improving the luminance distribution.

Prismatic panels
The function of a prismatic control element is to redirect light by reflection and refraction of controlled natural light, deeper inside the building. Prismatic panels are made of glass, polycarbonate, acrylic or polyester in various shapes, often inside a double glazed unit (Figure 3.14). In the 1940s and 1950s, prismatic panels were used to redirect diffuse skylight from near the sky zenith to the back of of the room [Hopkinson 1966]. The prismatic panels, on the market today, reflect incident light for a pre-defined cut-off angle while light is transmitted for the remaining angles of incident. Outside the cut-off range, transmitted light is altered in direction, intensity and colour dispersion, by the optical refraction of the prism. The prismatic panel redirects sunlight to the ceiling and increases daylight levels in the interior by diffuse reflection from the ceiling.

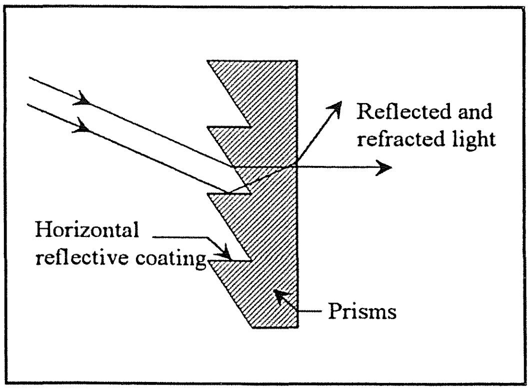


Figure 3.14 The prismatic panel used at BRE's daylight innovative evaluations [after Aizlewood 1993].

Measurements at BRE were conducted for a prismatic panel coated with a highly reflective material on one side of each prism [Aizlewood 1993]. Only a few days of the year, on a clear days with direct sun perpendicular to the window (± 20° solar azimuth angle) resulted in an increase of the work plane illuminance at the back of the room. Clear days in the summer or winter reduced the relative, interior illuminance level at the back by 30% (summer) and 50% (winter), compared to the reference room with a glazed area of equal size. In the summer, areas close to the window were shaded from direct sunlight by a reduced illuminance level of 70-80%. Measurements in autumn/spring increased the illuminance level by 100% in the back, but this was rarely replicated during the

For cloudy conditions, the admittance of diffuse skylight was partly rejected throughout the interior, causing the work plane illuminance level to be reduced by 35-40%.

Prismatic film
A prismatic film has a similar function as the prismatic panel, with optics as a fresnel or fine prism structure on one side and a flat surface on the other side. The prism is made of polycarbonate or acrylic, attached to a thin film, with a light transmittance of 89% and a refractive index of roughly 1.6. The geometry of the film is changeable, but BRE used a film with the prism angles of 62° and 78° [3M 1990 & 1991, Aizlewood 1993]. Clear days in the spring, summer and autumn increased the relative work plane illuminance level, mainly in the intermediate area by 20%. Winter solar angles increased the light levels close to the window and reduced the illuminance level at the back by 30-40%. An overcast sky reduced the interior work plane illuminance level by 10-30%, lowest at the back.

Holographic glazing
Holographic glazing is still in the development stage, using a transparent micron-thin coating, containing either silver-halide emulsion, dicromatic gelatine, photopolymers, or embossed thermoplastic, etc. [Baker 1993, Papamichael 1993]. The holographic technique is attached to the glazing to collect and redirect transmitted direct and diffuse solar radiation for a predefined acceptance angle. Early design of the holographic glazing introduced an undesired "rainbow" effect, but this effect has been improved producing "white" light with the trade-off by reduced diffraction efficiency. The diffraction efficiency is defined as the fraction of the incident visible radiation diffracted towards the ceiling. Experiments at Lawrence Berkeley Laboratory indicate that the diffraction efficiency for holographic glazing is estimated to be 16-20% for the most effective incident angle [Papamichael 1993]. Transmission of diffuse light was approximately 50-60%, due to the uneven thickness of the photographic emulsion over the plate.

Fixed or movable louvers and Venetian blinds
Louvers are a multiple series of horizontal or vertical slats of different size, either fixed or adjustable, situated on the exterior, interior or in between glazing (Figure 3.15). Horizontal louvers are often used on a south-facing window, while vertical louvers are used on east- and west-facing windows. Depending on orientation, sun elevation and slat angles, direct solar radiation and/or diffuse skylight are obstructed, reflected and/or redirected to the interior, changing the system's optical and thermal properties relative to the material used (diffusive or reflective). The durability of exterior slats depends on the material used to protect from the external conditions. The slats are usually made of galvanised steel (raw or painted), anodised aluminium, PVC, wood etc. Interior slats are usually small (Venetian blinds) or medium-scaled PVC, wood or aluminium. The main drawbacks with louvers are that they tend to block and frame the view outside and they usually stay down without any adjustment [Rubin 1978]. Behavioural studies with Venetian blinds show that occupants do not adjust the blinds optimally regarding natural light or preventing penetration of direct sunlight or thermal radiation in the interior. Automatically adjustable louvers increase optimal control of daylight and prevent penetration of solar radiation. However, automatically adjusted blinds produce a trade-off regarding the psychological effect of not having to control the louvers and this can influence the occupants' comfort and well-being.

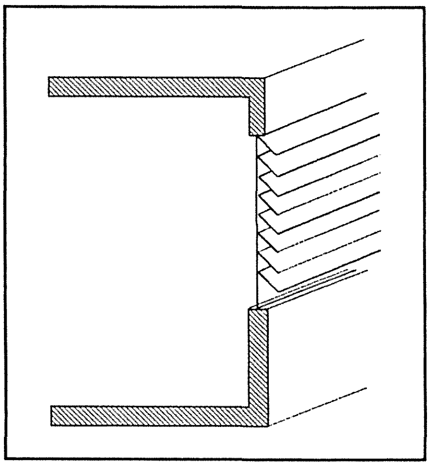


Figure 3.15 Venetian blind or louver shading the window for direct sun.

Louvers are usually situated on the exterior facade while Venetian blinds are fitted inside, designed as a movable, dynamic shading device to control admittance of direct solar radiation. Movable Venetian blinds and louvers in the building envelope serve as a complementary function by reflecting or redirecting direct or diffuse radiation. Blinds and louvers are designed mainly to control sunlight, reduce undesirable solar gain and glare while admitting visible light. Lately, the intention for using of Venetian blinds was also to "increase" the illuminance levels or at least reduce the non-uniform luminance distribution. Most designs of interior Venetian blinds will provide less interior light than that admitted by a clear, unobstructed glass. However, the system may redirect light from the window perimeter to the back of the room depending on the slat angle and material finish. Glare problems and visual distractions in the interior will depend on the slat angles, the material properties used and the distance between the slats. Therefore, adjustments of the blinds should accommodate daily and seasonal variations of the solar position in order to reduce undesirable solar gain and glare while admitting visible light.

Venetian blinds obstruct the view outside through a confining, bright, distracting structure. The structure can generate an annoying visual noise which detracts from the pleasure of the view. Large-scaled louvers will tend to frame the view, whereas medium-scaled louvers are often not large enough to frame or small enough to be perceived as a texture or patterns. The view-out function also changes, if the louvers are horizontal or vertical. Vertical louvers will reduce the horizontal width of the exterior view, but enhance the vertical view of the sky dome, while it is the opposite with horizontal louvers. Horizontal louvers (0°) describe the "non-screen" pass-through view of the exterior, while downward tilted louvers enhance the ground view and upward tilted louvers increase the sky view. Venetian blinds and louvers will always reduce the view-out function, but they can prevent interior discomfort glare because of the reduced solid view angle of the sky. However, visual perception of the exterior view frequently tends to create a figure/background conflict by a distracting visual field of undesirable confusion between the blinds and the view outside [Lam 1972]. This confusion can be reduced so the view is more interesting. On clear days, the Venetian blinds often produce extreme bright lines along the slats and tend to reflect light and dark bands at particular spatial frequencies causing visual distraction.

A fixed device, consisting of numerous, equally spaced reflective louvers in between a double glazed unit, was tested at BRE [Aizlewood 1993]. The reflective unit (Okasolar) is designed to reflect the light to the exterior when not needed, and partly to reflect and diffuse natural light without mirror effects. The system consists of three differently shaped sides (Figure 3.16), where each side reflects incoming sunlight and diffuse skylight for a predefined cut-off shading angle [Okasolar]. The design regulates the transmittance of direct radiation to the ceiling or the reflectance to the exterior, depending on the elevation of the sun. The function of the system reduces overheating problems in the summer by reflecting all direct radiation to the exterior. It accepts only diffuse daylight, and transmits direct radiation in the winter when solar gain is desirable.

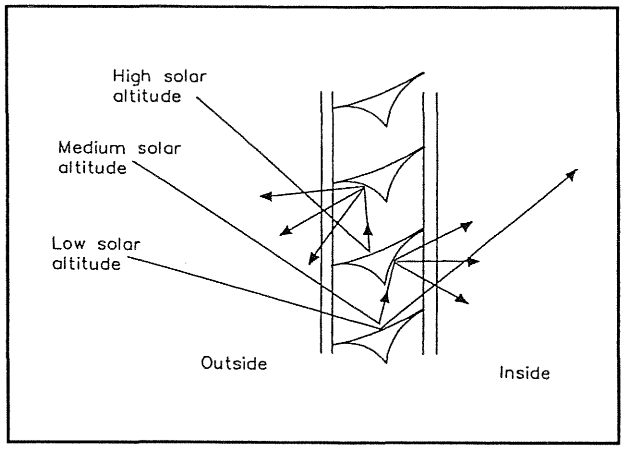


Figure 3.16 Fixed mirrored louvers in between glazing used at BRE daylight innovative measurements [reprinted from Aizlewood 1993].

Depending on the system design and the sun elevation, the manufacturer states that the light transmission is 5-60% for direct sunlight and 14-35% for diffuse skylight, with a shading coefficient varying from 0.24 to 0.77 [Okasolar]. Measurements at BRE with fixed reflective louvers, optimised due to the mock-up room's dimensions and orientation, showed for a summer situation and in between seasons, that the relative work plane illuminance level was generally reduced by 20-30%. In the winter, direct low angle sunlight penetrated the system and reflected light to the ceiling, increasing the illuminance level to almost the same as the clear glass in the back of the room. The reflected patch at the ceiling, from direct sunlight, was penetrating the interior deepest at noon (profile angle), while before or after noon, the reflected area moved toward the window. An overcast sky resulted in a performance reduction in the illuminance level of 25-45% with the least reduction at the back of the room.

3.5.3 Core daylighting systems

The intention of core daylighting systems is to beam direct sun exclusively to the interior where "normal" access by daylight is difficult to overcome either by an active or passive collector system. Innovative daylight solutions, reflective or refractive devices, are regarded as passive systems typically used in a side-lit office. The active systems track the sun by use of sophisticated optical systems channelling, guiding or concentrating sunlight to the interior building core [Leslie 1986, Whitehead 1986, Hastings 1994]. The concept of core daylight almost impeccably relies on direct sunlight, so the design applicability does not support climates like that in Denmark. Radiant heat from the collected sunlight may require filters or infrared-transparent mirrors to reduce and/or remove unwanted heat gain before entering the interior transport system [Littlefair 1990]. The transport system incorporates an optical system conveying the reflected sunlight beamed to the point of destination either vertically and/or horizontally. The interior light is released by a redistribution system, an emitter or luminaire, modifying the beamed sunlight to the interior, often diffuse to provide an uniform "sufficient" room lighting. At night or when there is insufficient exterior light, the light pipes are supported by an additional backup system, e.g. high-intensity metal halide luminaries, to light the offices. However, the backup system (discharge lamp) which repeatedly switches on when needed will cause interior problems by flickering and noticeable colour change. The main elements involved in a core daylight system are: a system to collect and/or concentrate sunlight (heliostat), a system to transport or pipeline sunlight and a system to distribute or emit sunlight to the interior from the transport system.

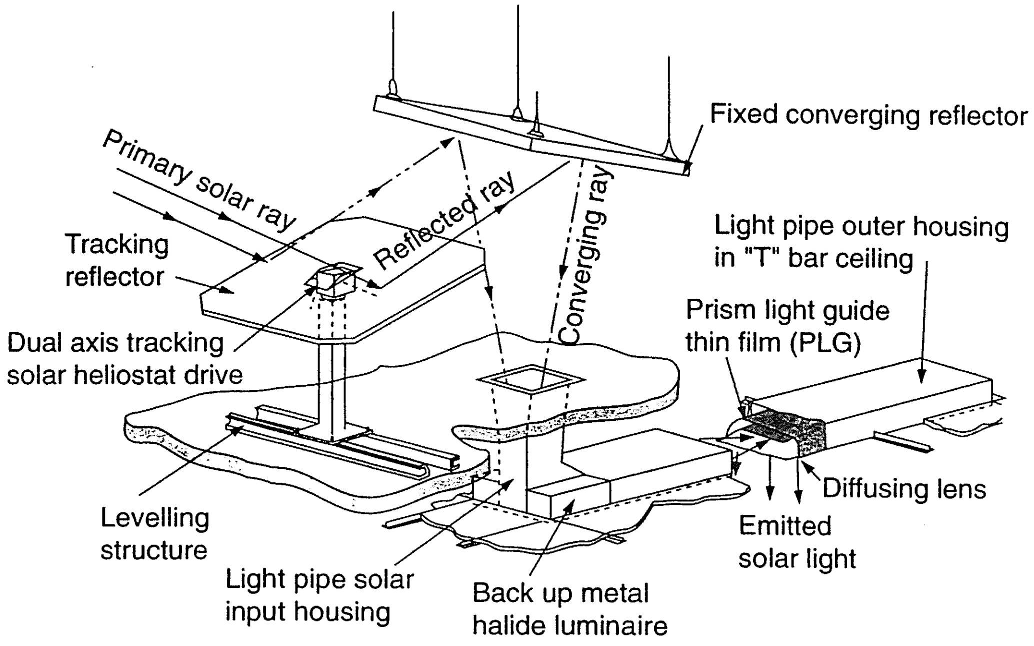


Figure 3.17 Pictorial of the heliostat/prism light guide system [Whitehead 1986, reprinted from Caddet 1991].

Heliostat

Most core daylight systems rely exclusively on sunlight, where Figure 3.17 [Caddet 1991] illustrates a sophisticated heliostat/prism light guide system in a transparent shelter. The heliostat system is situated on the roof to collect and redirect sunlight by a reflective tracking system, for a predefined solar orbit, through a fixed converging reflector to the light pipe unit. To ensure an almost concentrated parallel light in the light pipe unit, use of collimating optics may become necessary, and consequently reducing diffuse skylight suitabillity [Littlefair 1990].

Light pipes

Several common structures of light pipes exist (Figure 3.18), but the expense (fibre optics, acrylic rod) and colour emittance (liquid-filled tubes) narrow the options for using light guides to lenses, prismatic tubes, or reflective film [Schuman 1992 a]. A light pipe system transports natural light, except lenses or collimating devices, by utilising multiple internal reflection. The efficiency of the system depends on the material used (reflection coefficient), the transport distance, geometry of the pipe and angle of incidence for light entering the pipe. An empty shaft (such as light and sun ducts) is the simplest light pipe system, but the light transported will undergo multiple internal reflections, attenuating the light transport efficacy after a few metres. A hollow reflective light guide is basically a pipe or tube with an internal, specular mirror surface. Internal, collimated lenses are used to concentrate the beam, reduce excessive optical loss due to internal reflections and increase the pipeline efficacy and thereby light transport distance. A prismatic tube or film light guide is made of transparent, clear acrylic (sealed), empty square or rounded-section pipes, with the prismatic devices outside, parallel to the pipe axis. Interior light is scattered (impurities) and confined to the central air space due to internal reflection from accurately shaped prismatic grooves. Fibre optic cables, usually collected in bundles, transmit with high efficiency the light by internal reflections through a thin, quartz-based solid fibre. Optical fibers require little space and can be adapted to existing building structures [Hastings 1994]. Their transmission characteristics and colour rendition are good, but very expensive [Smart 1983]. A less expensive fibre optic is an acrylic rod (hollow or solid) [Fraas 1983], but the transmission is reduced. Liquid-filled light guides filter out the infrared radiation, but emit an unacceptable colour light dispersion in the interior.

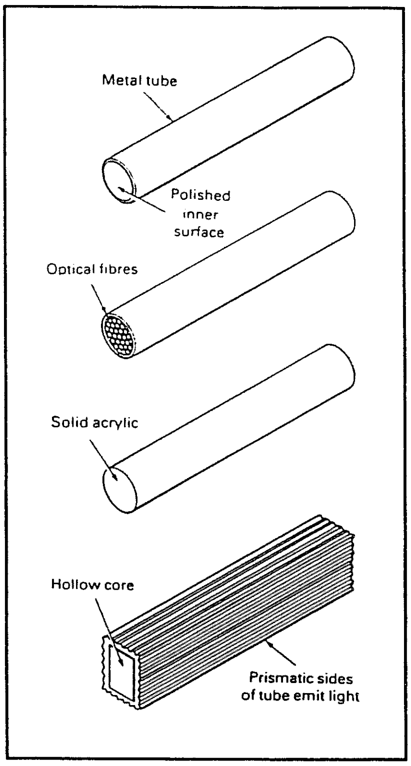


Figure 3.18 Different types of light pipes [reprinted from Littlefair 1990].

4. Visual Comfort

The qualitative aspects of human requirements for the interior environment are often expressed by visual and thermal "comfort", but there are few parallels between the two comfort criteria. An optimal thermal condition is the neutral perception of the interior environment, where occupants do not feel any need for changes towards warmer or colder conditions. Unfortunately, visual comfort is a more complex parameter related to receiving messages, instead of referring to a state of neutral perception of the environment [Baker 1993]. The main difference between the two comfort criteria is that visual comfort can always be improved, unlike the optimal thermal condition of the neutral perception. The criteria of visual "comfort" must therefore be interpreted as the clear reception of visual messages from the visual environment. Although Hopkinson recognised the complex nature of visual environment, he simplified the effect of environmental brightness upon visual comfort as: *"The term visual comfort is taken to mean the absence of a sensation of physiological pain, irritation or distraction. It is not intended to cover the aesthetic sensation of pleasure or dislike of the surroundings"* [Hopkinson 1963a]. The concept of visual comfort in this chapter, is only intended to present a brief description of visual perception and comfort criteria with respect to daylight design and analysis of the luminous environment.

The design of a comfortable and delightful visual environment depends on vision, perception and what we want to see in different room configurations and for different activities. An observer will receive visual information and perceive the interior in relation to the bounding surfaces subjected by their colour, texture and brightness, the furniture and its arrangement, and interaction between the interior and exterior environment together with a host of other details [Boyce 1981]. The stimulus of the information received, into an impression of the interior, is regarded as the visual environment [Canter 1975]. Earlier speculations of improving visual comfort were usually conducted by increased natural illuminance levels adequate for the intended task. However, this could lead to a false assumption revealed in a lack of understanding or knowledge of the function of the human vision and the complex relationship between human requirements and visual perception of the luminous environment. Therefore, "daylight design" must emphasise the importance of daylight used as an integrated and adopted part, not only with electric lighting, but also with the window system as part of the building envelope. The building design must therefore be coordinated, using adequate design tools, to produce an efficient and aesthetically satisfying interior, without ignoring other aspects of the environment affecting human comfort, *since it is difficult to judge the quantity of light, lighting design must be based on what one can perceive and what one wants to look at - the quality of the luminous environment* [Lam 1977]. Unfortunately most design tools are predominantly concerned with the physical values or ratios using a variety of approaches, and practically none of these are associated with design of a qualitative visual environment.

4.1 The vision

Vision, as a perceptual system, is the eye's ability to sense the visible light admitted through the pupil. Admitted light rays are converted into electrical signals and processed by the brain to provide visual information of light, colours and shapes etc. The light receives from an object form an inverted image at the light sensitive receptors in the *retina*. To protect the sensitive receptors and reduce the permittance of extensive bright light at the retina, the *iris* reduces the diameter of the pupil (Figure 4.1). Accommodation is the eye's ability to change the shape of the *lens* to focus light on the retina from near to distant vision [Baker 1993]. The retina contains light sensitive photoreceptors, *cones* and *rods*, where cones are predominantly located at the center while rods are more evenly distributed. Nerve cells transmit the signals received through the *optic nerve* from the stimulation of the photoreceptors. At the retina, cones contain colour sensitive pigments and perform the function of colour perception and accurate vision at normal luminance level (photopic vision). The eye's ability to see at low levels of light (scotopic vision) is provided by the rods, since rods are highly light sensitive but not colour sensitive [Hopkinson 1969, CIE 1987, Christoffersen 1993 a-b].

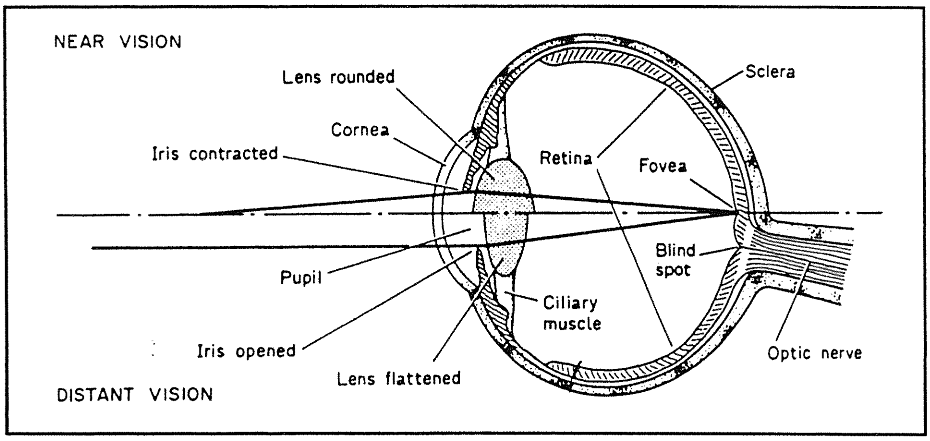


Figure 4.1 Illustration of the vertical section of the eye adjusted for near and distant vision [reprinted from Boyce 1981].

In the solar spectrum, only wavelengths between 380 nm to 780 nm cause a visual sensation depending on the amount of radiant energy received by the retina, although the eye is not equally sensitive to all radiation within the visible band. The relative spectral responsivity is defined by the CIE standard photometric observer as an *ideal observer having a relative spectral responsivity curve that conforms to the V(λ) function for photopic vision and to the V'(λ) function for scotopic vision, and that complies with the summation law implied in the definition of luminous flux* [CIE 1987].

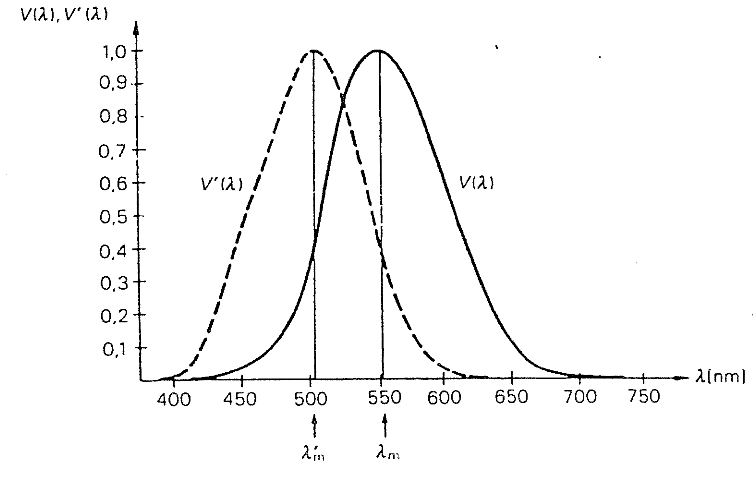


Figure 4.2 The eye's relative spectral responsivity curves to visible radiation: photopic vision V(λ) and scotopic vision V'(λ) [Reprinted from CIE 1987].

Photopic vision, illustrated by V(λ) curve, peaks for the light-adapted eye (> 2-3 cd/m^2) at 555 nm, which is the green-yellow region in terms of perceived colour (Figure 4.2). Low illuminance levels (night vision), cause the eye's sensitivity curve to be preferentially more sensitive to shorter wavelengths in terms of perceived colour (Purkinje phenomenon). Scotopic vision, displayed as the V'(λ), peak for the dark-adapted eye (less than 10^{-2} cd/m^2) at 507 nm because of the rod-dominated vision (i.e. red colours are perceived as dark). Intermediate vision between photopic and scotopic is called mesopic vision.

The field of vision can be separated into a central vision (*foveal*) and a peripheral vision (*foveal surround*) (Figure 4.3). Foveal vision endows, in a 2° cone around the center vision, the human eye with awareness and focus together with information on details and colours due to the concentration of cones. Peripheral vision (30° cone) provides quite high awareness and discrimination of brightness differences between an object and its background or foreground (rods) [Liljefors 1987]. However, the shape of the face, caused by the cheeks and the eyebrows, limits the peripheral vision to approximately 130° in the vertical direction. The upper limit in the vertical direction due to the eyebrowns is approximately 45°. There are usually no restrictions in the horizontal direction, resulting in an almost panoramic view of roughly 180° view angle [Fry 1969, Robbins 1986, Lechner 1992].

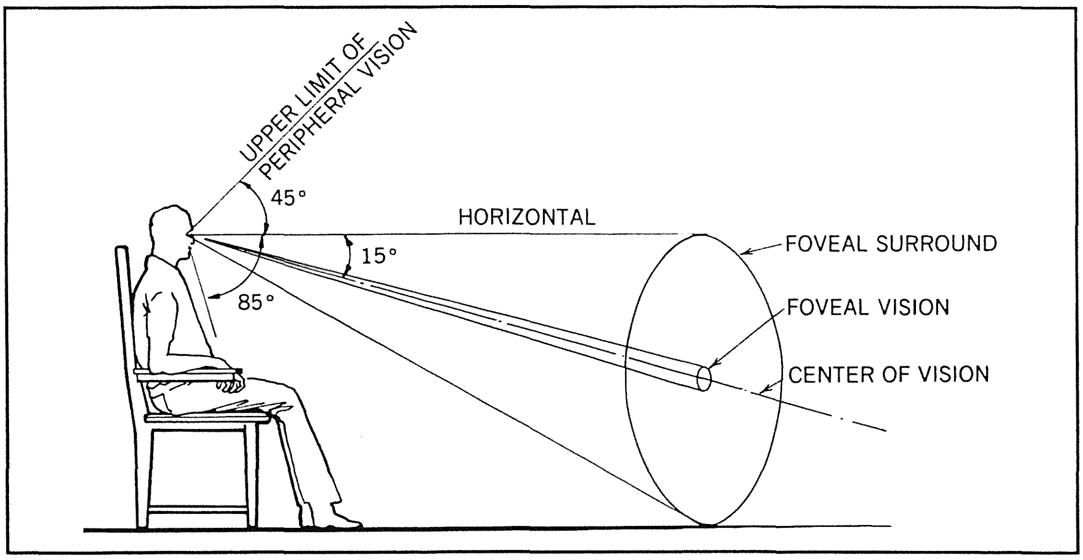
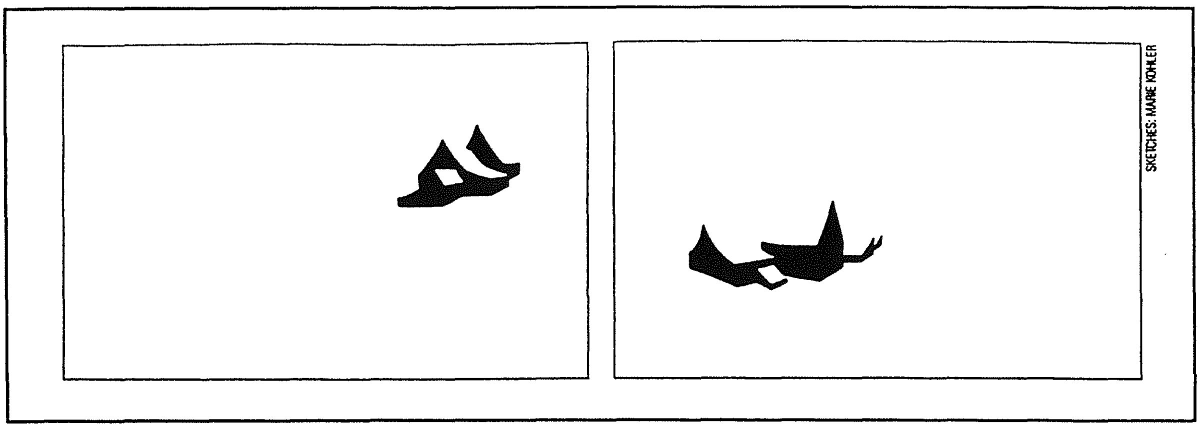


Figure 4.3 Center of vision and field of view where brightness ratios within the foveal surround (30° cone) must be carefully controlled [Reprinted from Lechner 1991].

Adaptation is the dominating characteristic of human vision, controlled by the sensitivity of the retina, to maintain the ability to see in moonlight as well as sunlight. CIE has defined adaptation as *the process by which the state of the visual system is modified by previous and present exposure to stimuli that may have various luminances, spectral distribution and angular subtenses. Adaptation to specific spatial frequencies, orientation, sizes, etc. are recognized as being included in this definition* [CIE 1987]. The retina can register luminance levels varying from 10^{-6} cd/m^2 to over 10^5 cd/m^2, while the luminance perception provides an adaptation ability normally limited to a brightness *range* of 1 to 1000 [Baker 1993]. The eye's ability to adapt is affected, not only by the range of brightness, but also the ability to see brightness differences, called contrasts [Hopkinson 1963a]. Contrast is usually described as the relationship between the luminance of an object and its immediate surroundings. In the luminous environment, a window can sometimes be perceived as "too bright" because the luminance level of the immediate surroundings in the visual field is too low. This can result in a sharp contrast between the adjacent walls and the window itself. However, increasing the luminance level of the surroundings may only produce a small noticeable increase in the perception of brightness, since the perception of light is logarithmic in nature [Hopkinson 1963a, Lam 1986].

4.2 Visual perception

Visual perception is an active, information-seeking process, partly conscious and partly unconscious, involving many mechanisms in a cognitive process interpreted by the eye and the brain. Lam described visual perception as *a meaningful impression obtained through the senses and apprehended by the mind which involves the combination of incoming sensations with contextual information and past experience so that the object or events from which the stimuli arise are recognised and assigned a meaning* [Lam 1977]. The visually perceived information from the luminous environment, illuminated by natural and/or artificial lighting, is interpreted by a combination of incoming sensations with contextual information of brightness, colour, distance, size, movement, perspective, etc. Any interference in the pleasantness of the perceived information is considered to be visual noise, which is an undesirable or disagreeable stimulus confusing, obscuring or competing with relevant, desirable or needed sensory information [Lam 1977 & 1986, Lynes 1978, Boyce 1981]. Figure 4.4 illustrates the difference between simple vision and complex perception, portraying dwellings seen in a snow scene [Erhardt 1991].



SKETCHES: MARIE KOHLER

Figure 4.4 The difference between simple vision and complex perception - the above objects portray dwellings in a snow scene [reprinted from Erhardt 1991].

The brain's perceptual psychology enables an associative translation ability, *constancies*, where changes in the visual environment are perceived unchanged. This permits objects, especially colour, size and shapes etc., to be seen and experienced similarly under different conditions even if the incident light is changed. Shape constancy is the brain's ability to recognise the shape of an object or pattern even if viewpoint, illumination, or distance is changed. The optical size of an object is measured by the solid angle from the eye subtended by the object of interest. Size constancy estimates the perceived object correlated by the immediate surroundings in which they are seen. A visual environment may appear to be of constant brightness since the brain makes adjustments to what the eyes see and compares the perceived information of an object with the immediate brightness of the surroundings. Brightness constancy is the ability to ignore differences in luminances under certain conditions. Colour constancy is the ability to eliminate the differences in colour due to variation of the incident light. If more than one type of light source is used in the visual environment, colour constancy is not possible, since the brain does not adjust to the colour balance of each source simultaneously [Lam 1977, Corth 1987].

Attractive brilliance is described as *sparkle*, but the brightness may interfere with the perception of other objects in the visual environment. The bright element can be evaluated as sparkling, romantic and desirable in one situation (candle, exterior view etc.) and glaring in a different situation, if the same element is evaluated to cause visual noise. These diverse, perceived effects illustrate the complex nature of psychological preferences combined with relevant physical variables, responded to and reacted upon, by the observer in the visual environment.

A window design fulfilling human physical needs and psychological preferences depends on the correlation between the physical, psychophysical and the psychological component [MacGowan 1980]. The *physical* component affects the physical indoor environment containing the window dimensions and location, the interior illuminance levels provided by natural and/or artificial light, the optical and thermal properties of the glazing etc. *Psychophysics* is the assessment of corresponding psychological magnitudes described by human observers (sensation) with the measured physical component (stimulus) [Tiller 1990]. Glare illustrates the magnitude of visible noise interfering the perception of visual information in the luminous environment, caused directly by an uncomfortable bright source of light or by reflections of the source in the line of sight. The discomfort glare index represents the concept of psychophysics combining physical values of the sky and interior luminances, the solid angle subtended by the glare source, manifesting the experienced psychological sensation. Interior visual discomfort caused by daylight, as a result of the luminance distribution, may perceive the window as "too bright", while the area at the back of the room as "gloomy". These visual descriptive impressions illustrate the complexity of the components influencing the visual perception of the luminous environment and the *psychological* preferences for view, daylight, sunlight, privacy, colour quality, geometry of the incident light, etc.

4.3 Daylight utilisation and psychological functions of the window

The main functions of the window are to allow the interrelationship between the exterior and the interior, to provide adequate interior natural lighting levels, natural ventilation, acoustic interchange and protection from the thermal exterior climate all year round. Use of natural light has a major interest because of its aesthetic possibilities and daylight's ability to satisfy biological needs and to address ecological concerns. Although daylight penetrating the thermal envelope, as a "free" natural resource, has an undisputed psychological positive impact on the occupants, the natural light is simultaneously associated with unavoidable side effects including the risk of overheating and glare.

Most of the research in the complex nature of visual comfort has been conducted with respect to commercial buildings because of its potential re-creation applicability to a number of similar office configurations. Conscious design for use of daylight in the interior also affects the shape and structure of the building, since the occupants typically have static working conditions (VDUs), restricted individual movements and high occupancy profiles. The challenge to the building designer when utilising daylight includes not only variability in light intensity and direction, but also the complexity of heat transfer through the window, daylight interaction with artificial lighting, as well as impacts on heating and cooling demands. Especially in the last decade, a renewed interest has emphasised the environmental and global issues, recognising that intelligent use of natural light and artificial lighting control strategies can contribute significantly to energy efficiency of buildings. The latest technology makes additional changes to the window envelope by integrating new daylight strategies "enhancing" daylight penetration to improve the luminance distribution in the interior. However, little research has been conducted with the intention of acquiring a higher profound understanding of the behaviour of natural light in the interior environment [Littlefair 1988 & 1990, Aizlewood 1993]. Even fewer have evaluated the interior qualities and consequences of introducing "new" technologies, aiming at increased utilisation of daylight by manipulating the optical properties of the fenestration elements.

4.3.1 Windowless office environment

The Danish building regulations do not allow windowless working environments. Some literature suggests that people are not particularly enthusiastic about windowless spaces since such environments produce variable reactions from passionate dislike to calm acceptance [Collins 1975, Wotton 1976]. The subjective reaction due to the elimination of windows submits the following response of dissatisfaction: *no daylight, poor ventilation, inability to know the weather, inability to see out and have a view, feelings of being cooped-up, isolation and claustrophobia, feelings of depression and tension* [Collins 1975]. These unfavourable reactions can perhaps be influenced by the size and geometry of the room, by the amount of time spent inside the room, whether the type of task performed is repetitive and boring, restricted individual movement and interaction with other employees etc. (i.e. secretaries). Such working conditions may contribute to a reaction that the interior conditions are unpleasant and oppressive, although these reactions are not all related to the elimination of windows.

The windowless environment may also affect various aspects of human health and well being. Natural light processed by the visual system activates both the sensory capacity of vision and the non-visual part of the brain, called the *suprachiasmatic nuclei*. The natural light is fundamental to the human biological clock (circadian cycle) and its associated daily rythms of sleep, temperature, hormone secretion etc. [Lærum 1988, Cawthorne 1994 a-b, Baker 1993, Bernecker 1994]. The seasonal variations at high latitudes, especially in the winter, may result in the syndrome called Seasonal Affective Disorder (SAD). To reduce the symptoms of lethargy and depression, caused by SAD, natural light in the interior is necessary since artificial lighting alone is insufficient to cause the necessary physiological response [Coleman 1986]. On the other hand, buildings supplied with daylight may provide sufficient light to reduce the SAD syndrome. A Swedish study assessed the effects of natural light and/or fluorescent light on school children, in four different classrooms [Küller 1992]. The studies were addressed to investigate the production of stress hormones, pupil performance, body growth and sick leave in environments with or without windows. It also included the impact of different fluorescent tubes, warm-white or daylight tubes. The results indicated that working in windowless classrooms, or spaces inadequately illuminated may cause disturbance to the chronobiological system regulating the production of hormones [Küller 1992, 1993].

4.3.2 Windows in the office environment

In the normal luminous environment, windows provide the view to the exterior and admit daylight to the interior causing an interior variability in direction of the "flow" of natural light. However, research in the reactions to the interrelationship between exterior and interior environment, has concentrated on the single topics, such as view, daylight, thermal comfort etc. Although all of these topics contribute to the satisfaction and psychological function of windows, few investigations have evaluated the total impact of windows [Canter 1975]. Furthermore, many of the investigations have been conducted in a static scale-model and not in real dynamic situations, enhancing the problem of generalisation of the results from one specific context to another [Ne'eman 1970, Keighly 1973a-b, Ludlow 1976, Roessler 1980].

View

View, as the scene beyond the window, repeatedly emerges as one of the most beneficial aspects to fulfil the psychological desire for windows. Appreciation of the exterior view is affected by the location and geometry of the window, the position of the observer in the interior, the content of the view, the contrast effect of the window frame and adjacent walls, height above the ground as well as age of the observer etc. The window view is also submitted as a "visual rest centre", permitting the eyes to relax when needed [Hopkinson 1963a]. Large windows will increase foreground view containing most of the detailed and informative portion of the view. Pleasantness of the explored visual information is provided when the window head is clearly above the skyline and the sill below the dividing line between the foreground (mainly horizontal) and the layer consisting of upright objects such as trees or buildings [Lynes 1974]. Design of horizontally shaped windows creates a horizontal view of a skyline, while vertically shaped windows enhance depth and view of the surroundings containing information about buildings and trees (vertical objects). Increasing the observer's distance from the window tends to produce a decreased satisfaction with the view. The view may appear framed by the window and reduce the three-dimensional, perceived reality of the exterior. Using shading devices will reduce the intended view and sometimes generate additional visual noise, eg. as experienced by the use of Venetian blinds. The blinds may disturb the external view as a result of the figure/background confusion, since the brain always tries to sort out the interesting visual signal (view) from the visual noise (slats). A diminishing effect to the figure/background confusion is increased view through the blinds [Lam 1977, Rubin 1978, Lechner 1992].

Studies of window dimensions

The acceptability of the exterior view is closely related to the dimension, position and shape of the window. Increasing the window dimensions will increase the exterior view, containing a greater depth, both in the foreground and at long distance. However, it will also result in increased energy consumption and side effects like increased daylight penetration, thermal discomfort, glare problems and reduced privacy, etc. Different research studies have examined "optimum" and "minimum acceptable" window dimensions, geometry and locations, in a static scale-model simulating real dynamic "scaled" situations. In these scale models, real situations are illustrated by miniature furniture and windows, explored either by real views or by pictures of different views. The simplicity of using scale-models is directed to a flexible investigation of the influential variables such as the view, window dimension, building orientation and type of glass. However, Ne'eman and Hopkinson addressed the problems of generalising the results from one specific context to another. They concluded that the results *might lead to false conclusions. Viewing through a scaled window might introduce another complication by dividing the observed view into mixed monocular and binocular fields. Furthermore, a difficulty might arise from the comparison between the dimension of the scaled model, especially the scaled window width, and the actual distance between the human eyes* [Ne'eman 1970].

Ne'eman and Hopkinson's investigations of *minimum acceptable* window size, used a full-scale model and a 1/10 scale-model of an open plan office [Ne'eman 1970]. The scale-model was placed at three different locations with 319 subjects viewing a real external environment through the scaled interior environment from a position corresponding to 5.5 m from the window. The minimum acceptable window size was determined as a function of the room dimension, the number of apertures, the outside view, the weather, external illuminance level, and the window height (1.5 m and 2.1 m) with sill height of 0.9 m. The results show that almost all parameters affected the observers' judgments of minimum acceptable window size. The use of a full-scale model revealed that judgement of *acceptable minimum* window size was influenced by the distance from the window, the height of the window and the content of the external view. An external view containing nearby objects increased the demands for wider windows (width = 3.1 m), while an external view of distant objects reduced the width (2.4 m). The authors concluded that the window height was less critical than the window width since the foreground view attracts and contains most of the detailed and informative portion of the view [Ne'eman 1970, Collins 1975]. They also found that the minimum acceptable window size was almost independent of interior illuminance from daylight, sunlight and artificial light and the angle between the line of sight and the window normal. The mean setting of window width with a fixed window height of 2.1 m was 2.4 m (window/wall ratio ≈25%). To achieve 85% acceptance among the observers, it was necessary to increase in the window width to 3.4 m corresponding to a window/wall ratio of approximately 35%. When increasing the acceptable window width, investigations showed critical judgments of acceptability for horizontal view angles less than 60°, while view angles outside this range were less critical and to some extent ignorable.

Keighley used an open plan office scale-model (1/12) to investigate the effects of reduced window area by projecting different colour transparencies simulating different views seen from various floor levels [Keighly 1973 a-b]. The studies were conducted in two phases; *preferred* location and shape of a windcw of fixed size (window/wall ratio = 20%), and *satisfactory* arrangements of several apertures covering 11-65% of the wall area. The results showed that preferred adjustments of the window shape and location were influenced by the external view. An external view containing foreground information increased the demands for wider windows located in the centre of the window wall. Window height preferences were determined by the skyline, varying from 1.8 m to 2.4 m with a sill height below eye level for a seated person [Keighly 1973 a]. Keighley also studied people's preferences of dividing a given opening area into several apertures. The results showed markedly negative responses to several windows of different sizes regularly arranged, since they broke up the external view.

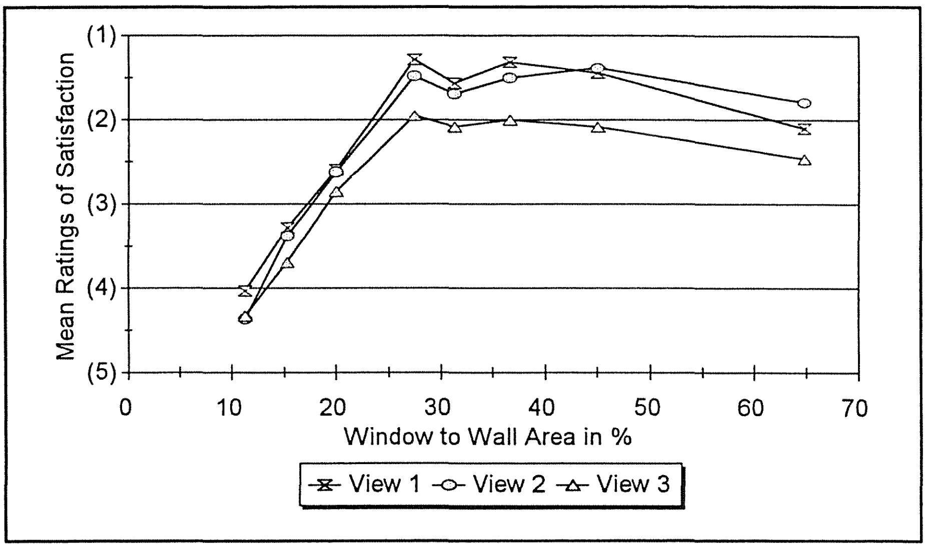


Figure 4.5 Mean ratings of satisfaction for a single window of different sizes for three different external views (after [Keighley 1973 b]).

The evaluations of satisfactory window size for three different views are graphically presented in Figure 4.5. View 1 is a distant city skyline, view 2 is a more restricted city scene and view 3 is a limited view occupied by an opposing facade. The observers described their satisfaction on a five-point rating scale. Using a multiple regression equation developed for each view, showed satisfaction with apertures occupying 25-30% of the window to wall ratio (Figure 4.5). The rating scale of *satisfaction* was labelled as, (1) = entirely satisfactory, (2) = fairly satisfactory, (3) = neutral, (4) = rather unsatisfactory and (5) = very unsatisfactory [Keighly 1973 b]. The horizontal axis expresses the window-to-wall ratio as a percentage, while the vertical axis gives the mean ratings of *satisfaction* for different window areas and views. Figure 4.5 shows *dissatisfaction* for glazed areas less than 15% of the window-to-wall area while almost complete *satisfaction* was achieved for glazed areas above 30%. However, it also showed reduced *satisfaction* with very large windows. These results are similar to those achieved by Ne'eman and Hopkinson, although the type of view was less important because of the static and limited nature in the photographic, external view.

Ludlow also used a 1/12 scale-model with light grey side walls. The experiments investigated the *preferences* for window size, shape and locations, when viewing the scale-model with 16 different photographs of the external views [Ludlow 1976]. The observers adjusted the prefered window dimensions of a single window (four shutters). The results predicted higher window area preferences, between 50-80% of the window/wall ratio, than Keighley, Ne'eman and Hopkinson. This difference may simply be a result of the assessments in the experiment of what is satisfactory and what is preferred, and/or the result of differences in the external views and the models used. Although the results show discrepancies in preferences for acceptable window areas, Ludlow also predicted a desire for wider windows if the external view had a distant panoramic view (H/W ratio equal to 1 : 2.4 m) while nearby objects with a higher skyline required a narrower aperture (H/W ratio equal to 1 : 1.4 m). These results are the opposite of the prediction found by Ne'eman and Hopkinson as a function of preferred external view.

One of the conclusions in Ne'eman and Hopkinson's investigation of preferred minimum acceptable window size, was that dynamic variation in the exterior view and the distance from the window seen by the observers (≈ 5.5 m) increased the need for wider openings. Discrepancies in the results relative to Keighley and Ludlow, may be due to the elimination of the dynamic effect of the exterior view by means of static photographs. Furthermore, the scale-model used by Keighley and Ludlow adapted an unrealistic distance from the window to the observer (≈ 17.7 m). The distance from the window observed may result in unrealistic adaptation abilities of the observer, relative to the interior luminance levels. This enhances the problem of generalising the validity of these results from one specific scale-model context to a realistic, interior office situation. Also, the "real" exterior view may influence minimum acceptable window size, since a relevant and informative view becomes more important when approaching the minimum acceptable dimension. Caution should therefore be taken regarding unquestioned implementation of these results since the investigations have been conducted and determined in a model, based on visual factors only, and the window envelope's thermal implications are excluded. Summarising the results of preferred and acceptable minimum window size, provides a recommendation of a symmetrical pattern of window arrangements occupying at least 25-30% of the window wall area.

Daylight and sunlight

Different studies have established results of higher preferences for daylight and sunlight to serve the visual environment, than from artificial lighting [Ne'eman 1974 & 1975, Jackson 1973 a-b, Longmore 1975, Boyce 1981]. Although daylight is experienced as universally desired, sunlight appears to create a whole host of psychological reactions and is often treated separately in the research of psychological preferences [Collins 1975]. Additionally, the culture and the climatic differences will enhance the discrepancies in the evaluation assessments of psychological preferences addressed to daylight and sunlight in the interior environment.

Daylight serves the interior with a variability in intensity, colour and direction constantly changing from sunrise to sunset, from day to day and season to season. Many believe that the variability of the daylight is the main quality of the window, providing an important psychological impact on the occupants in the interior. The complex appreciation of daylight in the interior can generate satisfaction in one situation while the same situation could be experienced as the exact opposite in a different context. Even if daylight is requested by all occupants, it may produce different reactions depending on the interior position, since people situated in areas near the windows may express less enthusiasm than if seated further away. The intensity and direction of daylight will also improve the modelling of objects and the ability to accentuate visual, three-dimensional perception of contextual information and appearance of, for example, brightness, colour, distance, size, movement, perspective, etc. [Jackson 1973 b]. One of the main qualities of daylight is the spectral composition, almost duplicating the human visual response to maintain reliable colour rendering. On the other hand, electric light may alter the perception of colours to match the spectral composition of the artificial light source [Lechner 1993]. Daylight will also increase a person's ability to differentiate foreground from background. However, this ability is diminished if the interior light is diffuse or shadowless, due to reduced contrast between the object and its immediate surroundings. Such environments can sometimes be experienced in a predominately artificially illuminated interior or if the sky is uniformly bright and featureless.

There is a common desire for sunlight in residential dwellings, while it has an entirely different psychological effect in non-domestic buildings, related to the implications which direct sunlight has on occupants with a given task at fixed positions in the room [Ne'eman 1975]. Most of the surveys of human preferences for sunshine in non-domestic buildings have revealed the desire for moderated and controlled sunlight, if precautions are taken to avoid visual or thermal discomfort. Awareness and reaction to sunlight is enhanced if the absence is associated with deficiency and duration in light or warmth [CIE 1990]. However, direct sunlight is often blocked or shaded to reduce interior discomfort, although sunlight enhances colour perception, three-dimensional form and orientation, weather conditions outside, etc. Ne'eman stated in his investigations that visual aspects of sunlight in buildings *inside adequately heated buildings, even in cold climates, the warmth of sunlight is not considered essential for thermal well being* [Ne'eman 1974]. The basic criterion for appreciation of sunlight in the building interior is affected by the duration of sunlight penetration. This desire will eventually increase for people living at northern latitudes [Ne'eman 1975, Collins 1975].

Control of daylight, sunlight and view

Daylight is often the preferred source of light in the interior environment, and daylight as a design parameter will have influence on the building construction and its design. However, the design will always be a balance between a solar control system reducing the risk of overheating against the need for natural illuminance and the benefit of passive solar heating. The energy crisis in the mid-1970's re-examined the potential for natural light in buildings, since the window was often addressed as the main source of both excessive heat loss and undesirable solar gain. It resulted, sometimes, in a reduction of the window area to control solar heat gain and reduce the energy consumption, but it excluded admission of daylight, the external view and if too small, created annoying glare spots [Hopkinson 1972]. Instead of consequently reducing the window area to reduce the energy consumption, Hopkinson conducted investigations in the 1960s and early 1970s on Permanent Supplementary Artificial Lighting of Interiors (PSALI) [Hopkinson 1959 & 1963a & 1966]. The idea of PSALI was to provide daylight near the window and artificial light in insufficiently daylit areas, although the results indicated difficulties in integrating natural and artificial light with visual comfort criteria [Roessler 1980, MacGowan 1980]. The outcome was, higher artificial illuminances near the window to reduce glare and achieve visual comfort, producing a "loss" in the incentive speculation of enhanced use of daylight to replace artificial lighting. Abandoning the PSALI approach, Hardy and O'Sullivan developed the Permanent Artificial Lighting system (PAL). The approach implemented a 10% glazing to wall area to maintain visual relief, contact with the exterior, thermal comfort and reasonable energy balance [Hardy 1967, O'Sullivan 1972, MacGowan 1980].

Another approach for controlling the admittance of solar radiation is the glazing unit itself. Use of tinted, mirrored and low-transmission glass in the window envelope caused a "new" type of problems, since they maintained alternation of the intensity and colour of transmitted daylight. These modifications to the glazing unit will especially affect the colour vision although the effect may be offset due to the brain's ability to maintain colour constancy. However, if no comparable and correctly coloured scene is visible in the field of vision, the perceived, altered stimuli from the selective glazing may not be recognised by the visual perception in the luminous environment. An adjacent view of colour and brightness perceived simultaneously with the selective coloured glazing (tinted) causes a noticeable and disturbing interference to the visual perception of the external view, because a more pleasing alternative is visible. Without available reference or comparison, the brain's perceptual psychology assumes dominance by the translation associative of colour constancy and perception process, reducing the unpleasant effect of coloured solar glass [Lam 1977]. At present, little investigation exists about the reactions and/or dissatisfaction regarding different types of tinted or reflective glazing. To summarise the knowledge discovered, solar glazing with low light transmission (10 - 15%) draws complaints about dark depression and annoyance with the external view, distracting reflections from the glass, but satisfaction with privacy in daylight hours while dissatisfaction at night time due to inverted view effect [Collins 1975]. Some positive aspects were: reduced needs for a shading device, reduced interior glare problems and increased thermal comfort by restricting undesirable summer sun. Instead of changing the optical properties of the glazing/shading devices accustomed to the climate in Denmark can be used. Curtains produce a personal taste and variation together with partly or totally blocking direct sun and diffuse skylight. It is also the shading device most likely to be opened by the occupant when needed. Venetian blinds can be closed completely, eliminating the view, glare, daylight and sunshine. They can be tilted to reduce direct glare, control daylight and allow directional view while "open" Venetian blinds allow full access for sunshine, daylight, and glare problems [Rubin 1978].

Privacy

Another topic related to the window design is privacy, since windows provide a view from the exterior to the interior, often recognised as being undesirable. The associated preferences of the window revealed in the context of privacy, can introduce a contradiction in a desire for smaller windows, less external view etc. However, some simple precautions could be movable shading devices and reflective, tinted or low-transmission glazing. The manually movable shading device will satisfy the psychological need of individual control affecting the occupants' comfort and well-being, while reflective tinted or low-transmission glazing may cause dissatisfaction at night time due to the inverted view effect.

4.4 Recommended interior luminance ratios

Although the eye's adaptation ability can adapt to large variations in brightness levels, it cannot adapt to very different brightness levels simultaneously. Visual stress and fatigue is often experienced when working with visual display units (VDU) caused by constant and rapid changes by eye movements between surfaces with high contrasting luminances [Perry 1993b]. The eye's sensitivity to brightness ratios is characterised by a higher sensitivity near the centre of vision, and lower sensitivity at the edge of peripheral vision. Acceptable luminance ratios indoors require knowledge of all the factors involved, from the light source itself to the reflectances of the interior surfaces (Table IV.1) [Boyce 1981, Baker 1993]. Controlling the brightness ratios in the field of vision can be accomplished by adjusting the reflectance factors of the surfaces, the illumination of surfaces and by avoiding dark backgrounds and/or distracting bright surroundings [Lynes 1978]. When designing an adequate interior for high visual performance in a normal work area, the submitted brightness ratios should not be greatly exceeded since both uniformity and excessive contrasts are not desirable. Uniform brightness (monotony) may support visual efficiency but also emotional fatigue, while excessive brightness may provide emotional acceptance, but impair visual performance. The task of interest should therefore be slightly brighter than the immediate surroundings to ensure attention and avoid distraction [Lechner 1993]. The brightness design ratios given in Table IV.1 should ensure a comfortable balance between the interior luminances and the surface reflectances of the room (see Figure 4.6 and Table IV.1) [Boyce 1981].

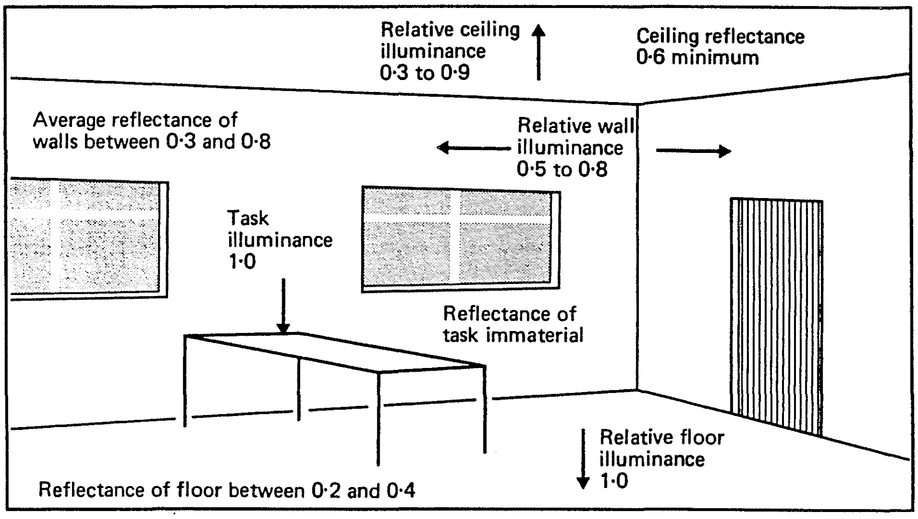


Figure 4.6 Recommended ranges of surface reflectance and illuminance ratios relative to task illuminance [reprinted from IES 1977].

Table IV.1 Recommended brightness ratios for indoor lighting.

Areas	Brightness Ratio
Task and immediate surroundings	3 : 1
Task and general surroundings	5 : 1
Task and remote surroundings	10 : 1
Light sources and too large adjacent area	20 : 1
Maximum contrast (except if decorative)	40 : 1

4.5 Glare

The aim of a good daylight design is first, to provide fully sufficient light for efficient visual performance, and second, to ensure a comfortable and pleasing environment appropriate to its purpose. The comfort aspect of a daylight design is closely related to the problem of glare [Hopkinson 1966]. Generally glare can be described as a subjective phenomenon caused by the magnitude of visible noise interfering with the perception of visual information due to an uncomfortably bright source of light in the field of vision. Measuring the magnitude of glare is only possible by characterisations and assessments from the observer involved, together with the physical factors determining the magnitude of the sensation. The CIE defines glare as the *condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable contrast* [CIE 1987]. Hopkinson defined glare, in general terms, as a condition of eye adaptation and contrast, that was unfavourable to vision, visual performance and perception, causing discomfort or impairment of vision [Hopkinson 1966, Baker 1993]. Glare is usually separated into the two components, direct glare and reflected glare, each causing detrimental effects to the ability of vision. *Direct glare is glare caused by self-luminous objects in the visual field, especially near the line of sight, while reflected glare is glare produced by reflections, particularly when the reflected images appear in the same or nearly the same direction as the object viewed* [CIE 1987]. The sensation of glare from artificial lighting will not be discussed in the present context, although the glare sensation caused by daylight is reproducible, to some extent, in the context of electric lighting.

4.5.1 Direct glare: disability glare and discomfort glare

The interference with visual performance caused by an unshaded light or a bright window, is called *direct glare*. There are two distinctly different forms of direct glare, *disability glare* and *discomfort glare*. CIE has described the differences as *disability glare is glare that impairs the vision of objects without necessarily causing discomfort and discomfort glare is glare that causes discomfort without necessarily impairing the vision of objects* [CIE 1987].

The difference between discomfort glare and disability glare can be described as the variation of the luminance across the visual field. A lighting situation can create disability and discomfort simultaneously, while different lighting conditions may cause disability and create discomfort independently. Disability glare occurs when light of high luminance is seen against a low luminance background close to the line of sight, causing the light to be scattered in the eye and generate a luminous veil across the retina. Disability glare depends on the size of the window, the line of sight, the brightness and intensity of the sky and sun and the contrast between the bright sky and dark interior [Hopkinson 1963a & 1966, Boyce 1981]. However, increasing the general level of brightness in the field of view by moving closer to the window will reduce the magnitude of disability glare.

Discomfort glare occurs due to the variation of the luminance across the visual field influencing the central and the peripheral visual field. This partly contradicts the discomfort glare index, since the index reduces the sensation of discomfort from a source by the displacement from line of sight. The peripheral vision is therefore sometimes expected to result in a failure to predict the magnitude of discomfort satisfactorily [Hopkinson 1970-71]. The magnitude of discomfort (not permanent) is more a result of the brightness of the source than its apparent size. Generally the brightness of the source caused by daylight have indicated a more tolerant assessment of acceptability than from an artificial lighting installation. This is usually explained by the external view's mediating factor even if the glare sensation was not reduced [Hopkinson 1963a-b & 1970-71 & 1972]. The discomfort glare index does not provide an absolute value that simultaneously covers the variability of external sky and sun conditions during the day and season and "all" the individual's subjective glare assessments in a specific luminous environment. This only illustrates the complex nature of daylight glare providing an illusion of an overall static discomfort glare model, describing the subjective assessment of the magnitude of the corresponding sensation.

Discomfort glare indoors is also caused by reflection, especially specular, from external surroundings and/or interior surfaces. This may cause a secondary sensation of distraction and annoyance if the glare source (sky and sun) is reflected into the field of vision. Approaching a light coloured interior environment (Lambertian surfaces), sometimes reduces direct and indirect glare due to an increased adaptation luminance caused by reduced interior contrast discrepancies. Reducing the contrast effect between the sky, seen through the glazing and the window itself, by light coloured window frames and glazing bars, will reduce the magnitude of discomfort glare caused by daylight.

4.5.2 Discomfort Glare Index

In the early decades of this century, investigations have been conducted to reveal the magnitude of experienced luminaires appearing too bright in the field of vision and causing visual discomfort [Perry 1993c]. Most of the recognised experimental research on subjective glare sensation was conducted in the 1940-50s at the Building Resarch Establishment BRE (England) and by Luckiesh and Guth (USA). In both experiments, trained observers were used to assess the sensation of glare. BRE used a scale-model simulating the glare from windows by a photographic, back-illuminated luminaire of a fixed range of brightness levels. The assessment of glare sensation was evaluated by observers adjusting the general background luminance level to achieve a predetermined degree of sensation [Petherbridge 1950]. Guth used a white hemisphere covering the field of vision with a single incandenscent source at the apex, simulating the glare source. Different adaptation luminances were projected at the hemisphere and the luminance of the glare source was rated at the borderline between comfort and discomfort [Luckiesh 1949, Guth 1952 & 1959]. The research described discomfort glare by the brightness of a small sourcs and the interior adaptation luminance. It resulted in an index describing the subjective assessments of the degree of discomfort caused by a glare source subtending a solid angle (ω_s) of $2.7 \cdot 10^{-4} \leq \omega_s \leq 2.7 \cdot 10^{-2}$ sr [CIE 1983 & 1992, Einhorn 1969 & 1979, Guth 1952 & 1959, Holladay 1926, Hopkinson 1963a & 1966, IES 1962, Luckiesh 1946 & 1949, Peterbridge 1950, Sørensen 1987]. A glare index describes the subjective magnitude of glare discomfort with high values illustrating uncomfortable or intolerable sensation of discomfort. It also provides the designer with an indication of how to control and limit glare discomfort. However, most of the equations developed do not (unfortunately) predict the sensation of glare from daylight accurately [Chauvel 1982]. At the moment, only the Cornell glare index predicts the combined effect of the physical values of size and position of windows (large glare source), sky and background (adaptation) luminance, the observer's line of sight, distance and position in relation to the window etc. The literature produces a number of equations for a single glare source, but all these equations can simply be described by eq. 4.1:

$$\textit{Glare sensation} = \frac{(\textit{Luminance of the glare source})^m \cdot (\textit{angular subtense of the glare source at the eye})^n}{(\textit{Luminance of the background})^x \cdot (\textit{deviation of the glare source from the line of sight})^y} = \frac{L_s^m \cdot \omega_s^n}{L_b^x \cdot p^y} \qquad 4.1$$

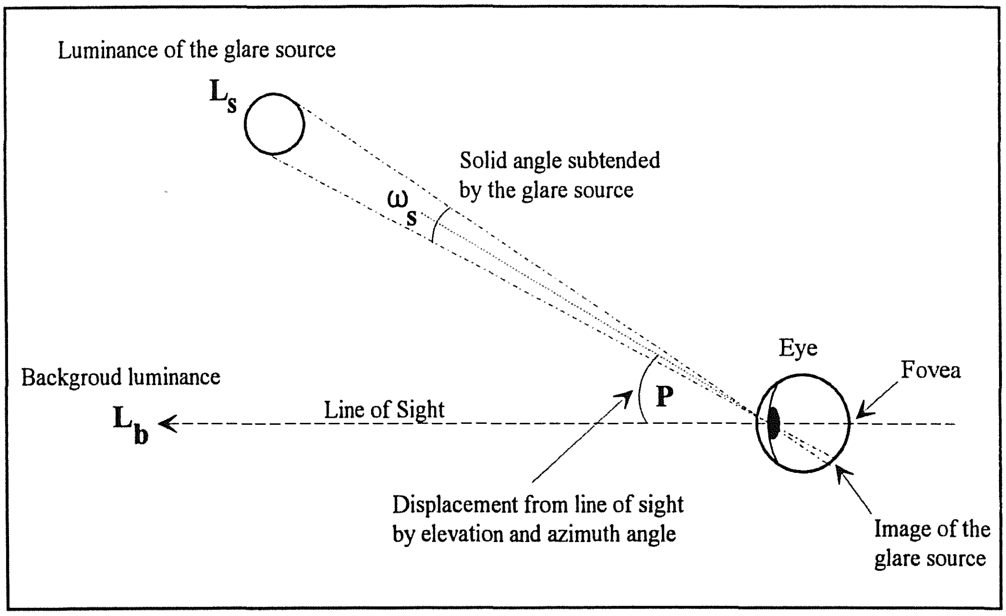


Figure 4.7 A simplified illustration of the parameters influencing the sensation of discomfort glare experienced (after [CIE 1983]).

Figure 4.7 illustrates the parameters influencing the sensation of discomfort glare for a simplified diagram of the eye. The image on the fovea is formed by the the object in the line of sight and the image formed by the glaring source in a different location on the retina [CIE 1983]. Equation 4.1 shows that, increasing the luminance of the glare source L_s and the solid angle subtended by the source (ω) while decreasing the elevation angle and azimuth angle (P) to the centre of vision, will increase the sensation of glare experienced. However, increasing the background luminance L_b would reduce the sensation of glare, supporting intelligent design and dimension of daylight windows. The simplicity of this analysis is not valid since the different factors can rarely be varied independently. Discomfort glare is usually a function of the following parameters:

L_s	Luminance of the glare source [cd/m^2]
L_b	Luminance of the background without the luminance of the glare source [cd/m^2]
ω_s	Solid angle of the source seen from the point of observation [steradian]
P	Guth's position index, expressing the change in discomfort glare experienced relative to the azimuth and elevation of the position for the glare source and the observer's line of sight
n	number of glare sources

The British glare index (BRE): BGI

The British glare index was developed by Hopkinson and Petherbridge in 1950 [Petherbridge 1950, Hopkinson 1963a & 1966, IES 1962]. The sensation of glare was evaluated by the following degree of sensations: just noticeable glare, just acceptable glare, just uncomfortable glare and just intolerable glare. The empirical formula (eq. 4.2) defines glare sensation from a single source:

$$BGI = 10 \log_{10} 0.478 \sum_{i=1}^{n} \frac{L_s^{1.6} \cdot \omega_s^{0.8}}{L_b \cdot P^{1.6}} \qquad 4.2$$

The Cornell glare index: DGI

The Cornell glare index is a modification of the BGI index, predicting glare from a large source (window). The study was conducted at the BRE and Cornell University (USA) [Hopkinson 1963 a-b & 1970-71 & 1972, Chauvel 1982, Boubekri 1992, Iwata 1992]. Evaluation of the Cornell glare index conducted by Cauvel concluded that *discomfort glare from a single window (except for a rather small one) is practically independent of size and distance from the observer but critically dependent on the sky luminance* [Chauvel 1982]. The degree of glare caused by any large glare source can be expressed by (eq. 4.3):

$$DGI = 10 \log_{10} 0.478 \sum_{i=1}^{n} \frac{L_s^{1.6} \cdot \Omega^{0.8}}{L_b + 0.07 \cdot \omega_s^{0.5} \cdot L_s} \qquad 4.3$$

where Ω Solid angle subtended by the source, modified for the position of the light source with respect to the field of view and Guth's position index P [steradian].

$$\Omega = \int_{\omega_s} \frac{d\,\omega_s}{P^2} \qquad 4.4$$

CIE's glare index (Einhorn): CGI

Einhorn developed a glare index (1979) adapted by the CIE, as a unified glare assessment method [CIE 1983, Einhorn 1969a & 1979, Lowson 1979]. The formula provides the steps of glare sensation on the CGI scale corresponding to the BGI scale (ranging from 10 to 30). The exponents in size and luminance of the glare source, expressed as $L_s^2 \cdot \omega_s$, where solid angle ω_s (exponent 1) is essential for additivity and subdivisibility while the exponent for the source of light L_s^2 (exponent 2) is based on experiments (eq. 4.5):

$$CGI = 8 \log_{10} 2 \cdot \frac{\left[\frac{1 + E_d}{500}\right]}{E_d + E_i} \cdot \sum \frac{L_s^2 \cdot \omega_s}{P^2} \qquad 4.5$$

where E_d Direct vertical illuminance at the eye due to all sources [lux]
E_i Indirect illuminance at the eye ($E_i = \pi \cdot L_b$) [lux]

CIE's Unified Glare Rating system: UGR

The CIE TC-3-12 has proposed an unified glare rating UGR system based on a modified form of the CIE glare formula. Glare prediction terms are slightly modified with respect to the BGI index [CIE 1992, Sørensen 1987a-c, Perry 1991a-c & 1993 c]. The intention of UGR is to compose the best parts of the recognised glare indexes in terms of the subjective glare response. UGR incorporates the Guth position index and combines the aspects of CGI and BGI to evaluate the glare sensation for an artificial lighting system, restricted to sources with a solid angle of $3 \cdot 10^{-4} \leq \omega_s \leq \cdot 10^{-1}$ sr (eq. 4.6):

$$UGR = 8 \log_{10} \frac{0.25}{L_b} \sum \frac{L_s^2 \cdot \omega_s}{P^2} \qquad 4.6$$

The American glare index (Guth): DGR

The final form of Guth's discomfort glare equation for an individual glare source was [Luckiesh 1946 & 1949, Guth 1951 & 1952 & 1955 & 1959 & 1963] (eq. 4.7):

$$DGR = \frac{0.5 \cdot L_s \cdot (20.4 \cdot \omega_s + 1.52 \cdot \omega_s^{0.2} - 0.075)}{P \cdot F^{0.44}} \qquad 4.7$$

where F Luminance of the background including the luminance of the glare source [cd/m^2]

DGR for a multiple source installation was given by [Guth 1959 & 1961] (eq. 4.8):

$$DGR = \left(\sum_{i=1}^{n} DGR_i \right)^{a} \qquad 4.8$$

where $a = n^{(-0.0914)}$ and n is the number of glare sources included in the calculation

The DGR system was used to define the percentage of people assessing an installation to be at or more comfortable than the borderline between comfort and discomfort, also called the visual comfort probability (VCP) [Guth 1959 & 1963 & 1966, MacGowan 1969, CIE 1983]. High levels of VCP predict increasing acceptability of the glare performance from an installation. The VCP glare scale is inverted relative to the BGI scale [Perry 1993 c]. The scale defined by the British system demonstrates that one glare index unit is the least detectable step and three glare index units are the normally acceptable step [CIE 1992]. However, some of the criticisms to the experiments conducted at BRE and by Luckiesh and Guth are: its applicability to ordinary observers, the time of adaptation to the experimental conditions before assessments of discomfort, the "leading" nature of the instructions given and the criterion technique of subjective appraisal [Hopkinson 1963, Boyce 1981]. The criticisms regarding the criterion technique are simply that observers tend to match the middle of the rating scale with the middle of the conditions experienced [Poulton 1977, Boyce 1981]. Although the recognised empirical models of discomfort glare provide the designer with an indication of advice, they are based on lighting technology current at the time of developments, "reducing" their applicability of glare calculations of today's lighting technology, working conditions and activities (VDU) [Perry 1993 c]. Table IV.2 shows for different glare indexes the magnitude of discomfort glare corresponding to the visual comfort probability (VCP).

Table IV.2 Comparison of the corresponding magnitude of discomfort glare experienced for different glare indexes with the visual comfort probability (VCP).

Corresponding degree of Glare	**BGI** **CGI** **UGR**	**DGI**	**DGR**	**Comfort VCP %**
No Glare			< 20	
Unnoticeable	< 10	< 16	35	95
Just imperceptible	10	16	50	87
Acceptable but not imperceptible	13	18	65	75
Just acceptable	16	20	90	64
BCD	18.5	22	**120**	**50**
Just uncomfortable	22	24	220	20
Uncomfortable	25	26	300	11
Just intolerable	28	28	400	5
Intolerable			700	

4.5.3 The Danish standard DS 700

The directions for artificial lighting in workrooms with desired worksurface illuminance [lux] are normally based on national codes or recommendations for daylight and artificial lighting in working rooms. In Denmark, these directions are for a general type of activities in the interior shown in Table IV.3 [DS 700 1986]. A typical office will have a desired work surface illuminance from 200 lux till 500 lux depending on different types of interior, tasks or activities.

Table IV.3 Selected directions for artificial lighting in workrooms with desired worksurface illuminance [lux] is normally based on the Danish Standard DS 700.

Type of interior, task or activity	**Illuminance level at the visual task of interest [lux]**	**Glare Index for artificial lighting system [BGI]**
Office:		
Continuous performance of visual task - writing, typing, reading etc.	500	17 - 20
Occasionally performed visual task	200	17 - 20
Conference and meeting rooms	200	17 - 20

4.5.4 Glare from reflection

Reflected glare arises when the light from a bright source is reflected off a surface directly into the eye or into the field of view from a glossy table, a reflective innovative daylight system, polished floors etc., submitting a similar effect and magnitude as direct glare. The reflected glare is often best avoided by a flat or matte finish producing diffuse Lambertian reflections instead of specular reflection. This is one of the reasons why specular surfaces are often avoided in a daylight design in the interior environment. However, innovative sidelighting technique often uses specular surfaces to reflect light deeper into the building interior, but precaution is necessary and usually solved by locating the system above the eye levels of a standing person.

Veiling reflection is defined as *specular reflections that appear on the object viewed and that partially or wholly obscure the details by reducing contrast* [CIE 1987]. The difference between veiling reflections and discomfort glare is the location of the glare source causing discomfort submitted by the reduced contrast necessary for acceptable visual performance [Boyce 1981]. It has its maximum if the angle of incidence from the light source is equal to the angle of reflection set by the position of the eye. It can be illustrated by the image of a window or luminaire reflected off the VDU screen, rendering the task of interest displayed on the screen impossible to see and assessing a form of disability glare.

5. The Daylight Laboratory

To take full advantage of all the benefits offered by daylighting, it is necessary to acquire a deeper understanding of the behaviour of natural light in the interior environment. A traditional window will disperse a non-uniform illuminance distribution while an innovative sidelighting system will change the "optical" daylight distribution, causing a reduced discrepancy between the window perimeter zone and areas far from the window. Innovative sidelighting systems aim at controlling daylight levels and solar gains in the window perimeter zone while enhancing the daylight penetration areas. The intention is to increase the use of daylight and replace artificial lighting in comparison with a traditional window without compromising visual quality and thermal comfort.

5.1 Design of daylight laboratory

Experimental assessment of the daylight systems has been carried out in two sparsely furnished mock-up offices (Figure 5.1), the daylight laboratory. The daylight laboratory, situated at the Danish Technological Institute (DTI) in Høje Taastrup, consists of two almost identical, south facing rooms: 3.2 m wide, 6.75 m deep, and 3.1 m high. The rooms are orientated 15 degrees west of due south, which allows near maximum amounts of sunlight to fall on to the glazing. The rooms appear almost like standard offices at DTI, also used for meetings and education, with colours of the carpet, walls and ceilings commonly used in normal offices.

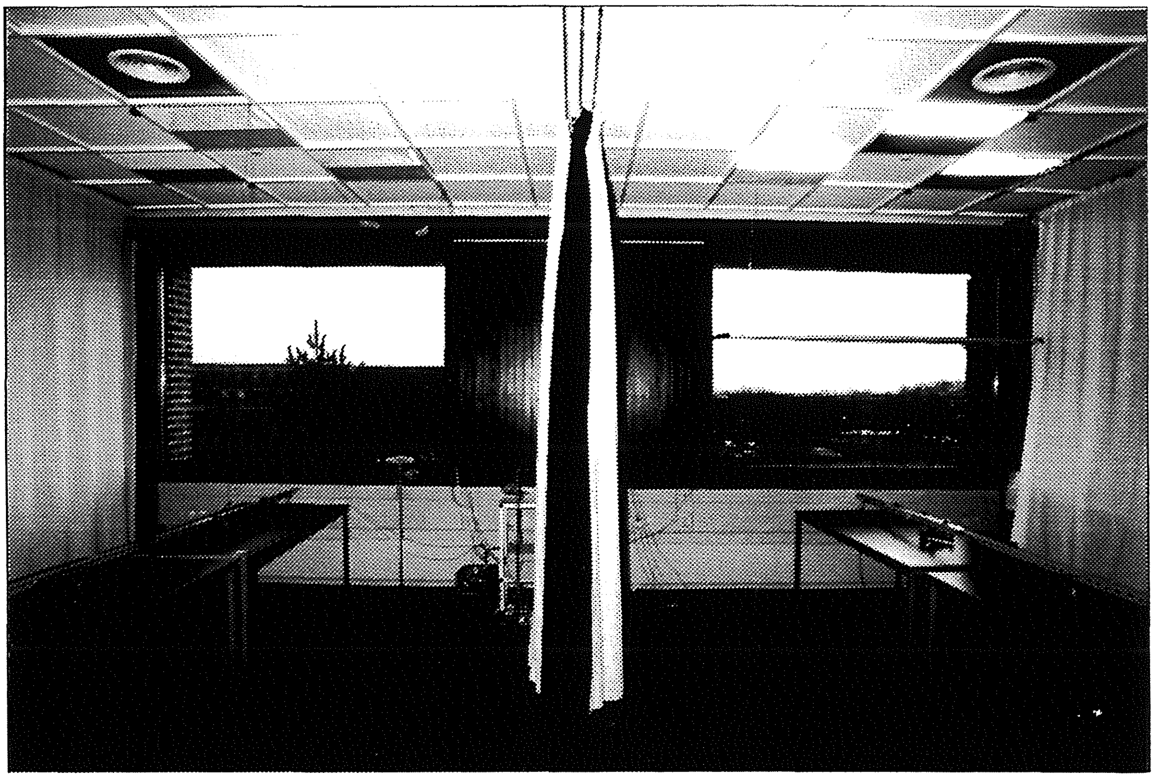


Figure 5.1 Interior photograph of the daylight laboratory with the reference room at left. Note the windows' different location in the facade relative to the separating interior wall (curtains).

The rooms have windows to the south with a glass area of $1.54 \cdot 2.16$ m^2 (without crossbars) and a light transmission of 80% (conventional double-glazing), one room adapted for experimental measurements of daylighting systems (test room), the other as a reference room. The window-sill height is 1.1 m above the interior floor level. The rooms are not perfectly identical, because the windows are not located symmetrically in the facade, but symmetric in relation to the separating interior wall (white curtains) (Figure 5.1). In front of both windows, a downward tilted window-sill extends with a depth of 0.45 m (ρ = 0.30) and an exterior overhang with a depth of 0.45 m (ρ = 0.30) at a distance of 0.1 m above the glazing. Additionally, there is an exterior vertical side fin extending 0.4 m from the exterior facade (ρ = 0.20) to the left in the reference room and to the right in the test room.

The reflectances of the floor and ceiling are fixed, whereas the reflectance of the side walls can be changed by using different curtain materials forming the wall surfaces. Measurements of the surface reflectances were conducted by a luminance meter and the reflectances are as follows:

■ Left wall	63 %
■ Right wall	82 %
■ Front wall (black)	5 %
■ Front wall (grey)	42 %
■ Rear wall (red bricks)	≈40 %
■ Floor	8 %
■ Ceiling	89 %

Some trees are positioned in front of the laboratory at a distance of 10-20 metres (Figure 5.2). The foliage will consequently cause some shading of the windows in the laboratory. Furthermore, cars were parked at a distance of 30-50 metres from the laboratory and unfortunately reflected direct sunlight to the ceiling. The effect of these situations was not significant under overcast conditions but affected measurements for direct sunlight. However, the presence of these situations will not affect the validity of the measurements.

Figure 5.2 Exterior view in front of the daylight laboratory (taken from the roof).

5.2 Monitoring equipment and degree of accuracy

Exterior sky measurements were carried out with four exterior detectors mounted on a horizontal roof with almost free horizon, of which two detectors measured horizontal global and diffuse sky illuminance (shadow ring). The remaining two detectors were mounted on the facade by a separating horizontal black screen (0.8·0.8 m), i.e. one measured the vertical sky illuminance striking the facade and the other measured the exterior reflected ground illuminance (Figure 5.3).

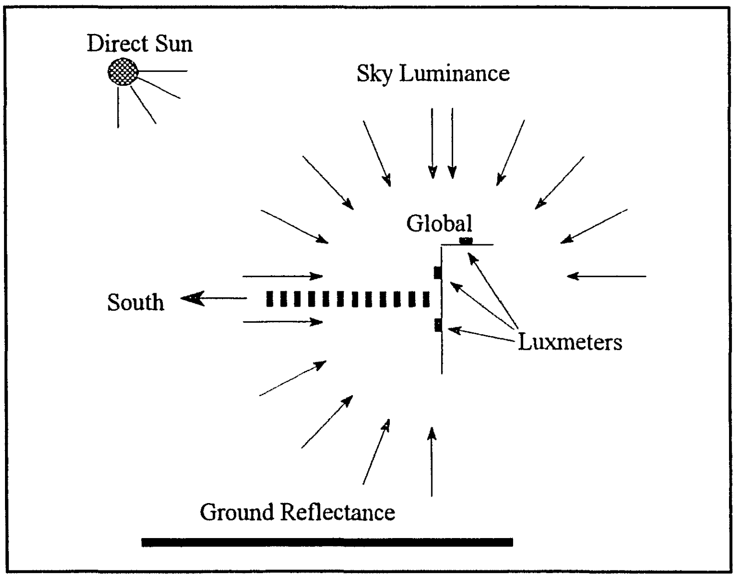


Figure 5.3 Principle drawing of exterior measurements: global, vertical sky and reflected ground illuminance.

Diffuse sky illuminance received on a horizontal surface from the hemisphere was measured on a detector with a shadow ring (Kipp & Zonen CM 121). The CM 121's sliding bars (see Figure 5.4) and the axis of the circular shadow ring, were parallel to the polar axis and manually re-adjusted on clear days by observing the shadow of the ring. Re-adjustments of the shadow ring were necessary at regular intervals (after a few days) due to changes in the sun's declination. The measured diffuse sky illuminance was corrected by a theoretical expression for the part of the diffuse sky which was screened off from the sensor by the shadow ring [Kipp & Zonen]. The specifications of the CM 121 are as follows: ring outer diameter is 620 mm with a ring width of 55 mm.

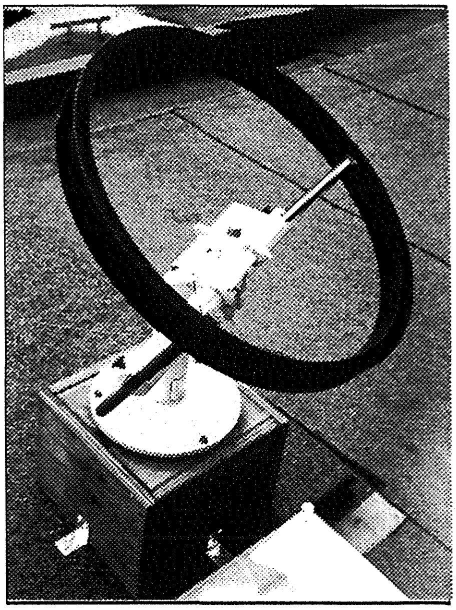


Figure 5.4 Photograph of the CM 121 shadow ring (Kipp & Zonen)

In the daylight laboratory, six illuminance detectors were positioned at the level of the working plane and five detectors on the ceiling (Figure 5.5). Within the rooms, the illuminance levels on the horizontal were measured by detectors in the symmetry line of the window at a work plane height of 0.85 m [DS 700 1986] at distances of 0.6 m (2), 1.2 m (3), 1.8 m (4), 3.0 m (5), 4.2 m (6), 5.4 m (7) from the window. The detectors mounted on the ceiling were regularly spaced at a distance of 0.6 m (8), 1.8 m (9), 3.0 m (10), 4.2 m (11), 5.4 m (12) (Figure 5.5). In addition, a vertical detector was placed inside the window surface (1) and 2 digital luxmeters and a luminance meter, both with analog output were used for spot measurements.

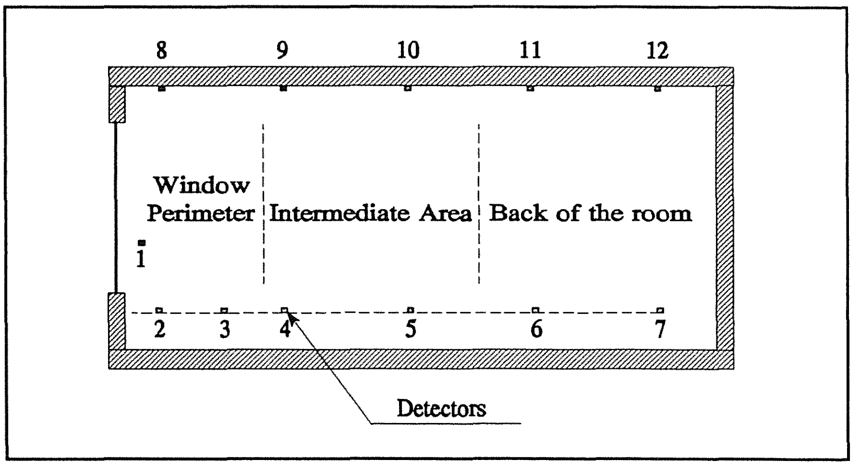


Figure 5.5Principle illustration of the location of the interior detectors.

5.2.1 Accuracy of the detectors

All detectors used for interior and exterior illuminance measurements were light sensitive silicone diodes from Hagner AB in Sweden. The detectors produce a small current which is converted to an analog voltage output signal (0-2 V) readable by the datalogger (CM 10). They were connected via amplifiers divided into 4 units each having 8 to 16 channels calibrated to the individual detector for a predefined illuminance range (Table V.1). The output signal was recorded by a datalogger every 10 seconds and averaged for 1 to 10 minute intervals during daylight hours. The short intervals were used when measuring the Venetian blinds for different slat angles. The bulk of the wiring across the room to the datalogger was carried out with coaxial cables to avoid interference and to keep wiring losses to a minimum.

Table V.1 Each output-channel was calibrated according to a predefined illuminance range to respond "accurately" for illuminance values in the interior.

Interior detectors	**Detector No. 1 [lux]**	**Detector No. 2 [lux]**	**Detector No. 3-12 [lux]**
Range	0 - 100.000	0 - 20.000	0 - 4.000

In the interior, the illuminance level can vary from less than 50 lux at the back of the room to more than 50.000 lux near the window depending on sky conditions and time of the day. In Denmark, overcast and/or partly cloudy skies are the main source of light, so the output voltage (0-2 V) for the interior detectors was calibrated to respond accurately for low illuminance levels (Table V.1). In situations with high illuminance levels, especially with direct sunlight, the aim of the study was to evaluate the shading ability of the sidelighting systems. Therefore, detectors in direct or reflected sunlight will be in a state of saturation for high illuminance values.

Daylight measurments can involve significant experimental errors depending on the accuracy of the instrument used, since the detectors were not all identical and their current output was not always directly proportional to the angle of incident. Two digital luxmeters (Hagner E2X), calibrated with the Hagner LS1-60-C luminance standard, were used to control the exterior and the interior detectors. Before being mounted on the work plane and on the ceiling, all interior detectors were checked by using the two lux-meters. The interior detectors were placed between the two lux-meters at the window perimeter and at the back of the room. For the two different angles of incidence, the control measurements showed no significant differences in the illuminance level. During the measurements, the interior detectors were covered to control the zero-reading and discrepancies were corrected and adjusted in the data logger.

Figure 5.6 shows that the interior and exterior detectors had a good cosine corrected response for most angles of incidence, where the *cosine law of illumination* indicates increased light sensitivity for high angles of incidence. However, interior daylight measurments are "less" affected by the cosine response, since high angles of incidence often coincide with low daylight illuminance values. Also, the illuminance level at the back is almost equally affected by the direct component and the inter-reflected component from all angles of incidence, thus reducing the significance of the cosine error. Exterior measurments include both direct and diffuse illuminances from all common angles of incidence. The manufacturer has therefore designed the external detectors to be cosine-corrected by rotation symmetry, causing the detectors only on be dependent on the angle of incidence and independent on the azimuth angle.

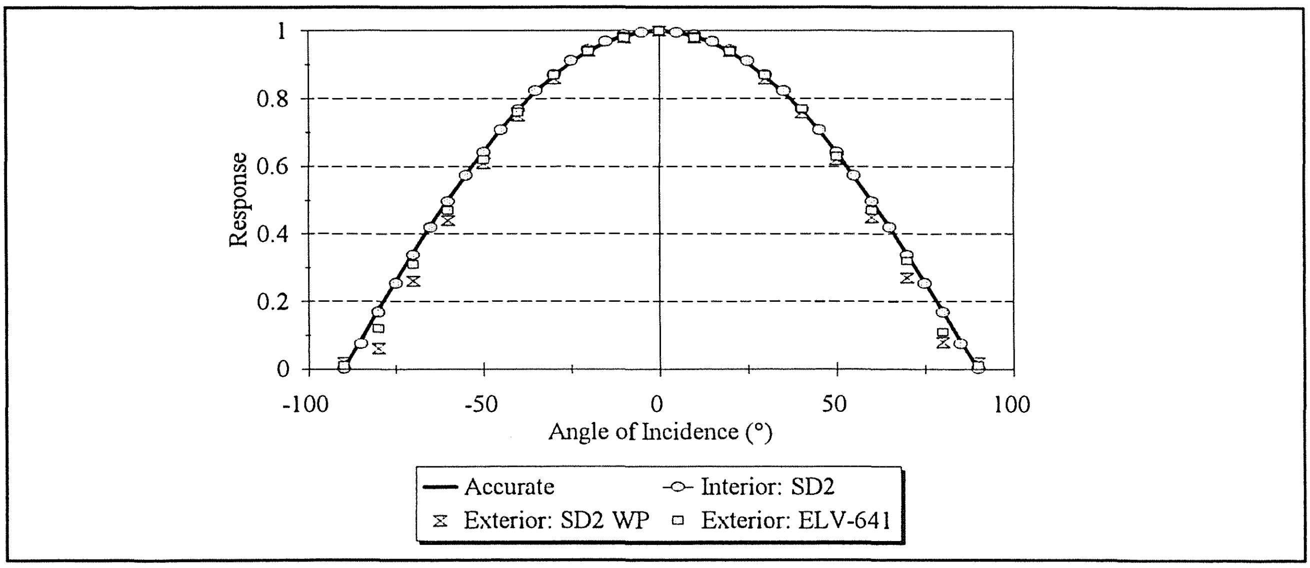


Figure 5.6 The cosine law of illumination shows increased light sensitivity for high angles of incidence [after Hagner].

The detectors were also filtered and adapted to produce the same spectral response characteristic of an average human eye (CIE standard observer, V_λ-curve). The instrument was calibrated by the manufacturer in "standard light A" (incandescent light). Figure 5.7 shows that the spectral sensitivity of the Hagner luxmeter is almost coinciding with the visibility curve of the CIE standard observer.

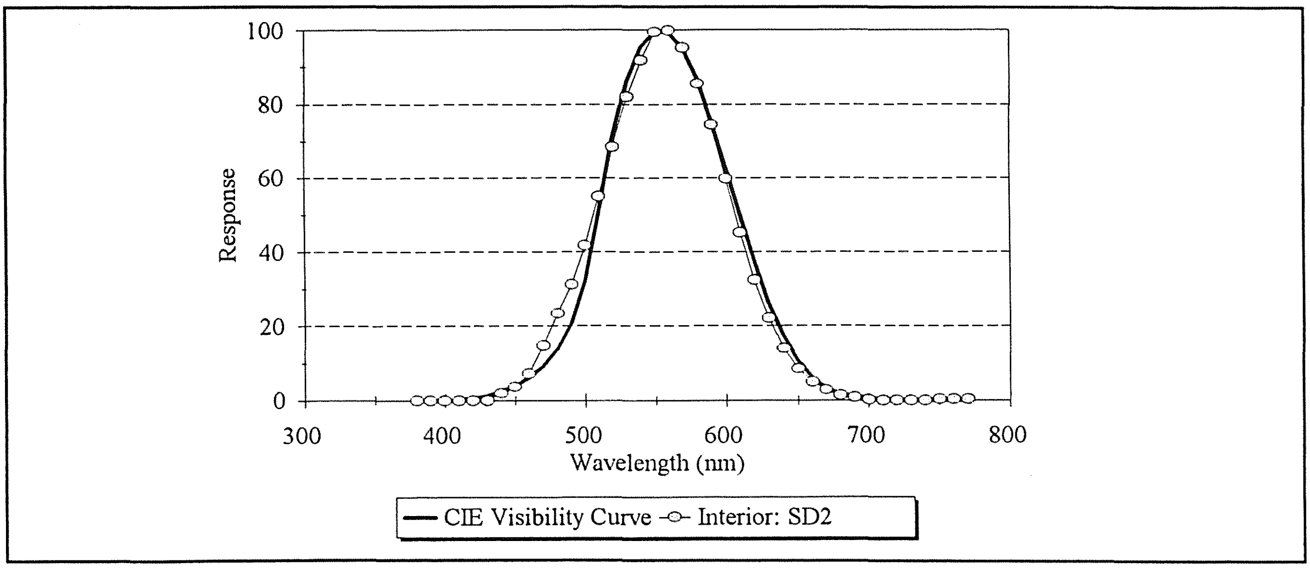


Figure 5.7 The spectral sensitivity of the Hagner luxmeter is closely related to the visibility curve of the CIE standard observer [after Hagner].

5.2.2 Degree of accuracy of the daylight measurements

The rooms were as far as possible designed to be similar, but there were some discrepancies in the measured illuminance levels due to the distance from the adjacent walls caused by the asymmetrical position of the windows in the facade. The variations between the test room and the reference room for the overcast sky and the clear sky are shown in Table V.2. Two statistical parameters are used to describe the accuracy of the measured illuminance levels: the arithmetic mean (mean) and the standard deviation (STDS) for all the illuminance values. The table shows the ratio of the measured illuminance levels in the test room to those in the reference room at the work plane and on the ceiling. These values show that the differences between the two rooms had almost no influence on the illuminance levels for the overcast sky conditions but affected measurements for the clear sky with direct sun, mainly because the interior illuminances were influenced by the interior inter-reflection from the nearby partition wall surfaces.

Measurements for the clear sky with direct sun were conducted in July 1994. In the table, "noon" refers to the average interior illuminance levels from one hour before and to one hour after the solar azimuth angle was perpendicular to the building facade. The morning and afternoon measurements are the average values of two hours before and after "noon". The ratio at 0.6 m on the work plane is not shown, since the detectors were in direct sunlight, causing the detectors to be in a state of saturation. A significant difference occurred with the detector on the ceiling in the test room at 5.4 m from the window. The detector showed a constant underestimation by a factor of 1.7 compared to the reference room, for the overcast and the clear sky conditions, so all values of this sensor in the daylight room have been adjusted by this factor.

Interior measurements for the overcast sky condition produced only small differences between the test room and the reference room. Table V.2 shows that the distribution of daylight entering the room throughout the day remained almost independent of the asymmetrical window location in the facade. Except for the detector on the ceiling at 5.4 m (12) in the daylight room, the small variations between the two rooms gave no occasion for adjustments of the interior illuminance measurements, since there were only insignificant differences between the interior measurements.

Interior measurements for the clear sky (July 2nd) with direct sun, were mainly conducted with the solar azimuth angle perpendicular to the building orientation (noon). This allowed near maximum amounts of sunlight to fall on the glazing and minimise the effects of the asymmetrical window location in the facade. Due to the continuous variations in the exterior weather conditions, some of the measurements had to be carried out at equal time separation from "noon", in the morning and afternoon, respectively. These measured values were added together to reduce the significant difference between the two rooms.

Table V.2 Ratio of illuminances in the test room and the reference room for Overcast Sky and Clear Sky.

Illuminance ratio	**OVERCAST**		**CLEAR SKY**					
Test room / Reference room	Mean	STDS	Morning Mean	Morning STDS	Noon Mean	Noon STDS	Afternoon Mean	Afternoon STDS
Work plane								
0.6 m	0.98	0.009	1.15	0.019	-----	------	-----	------
1.2 m	0.96	0.008	1.09	0.009	1.01	0.043	0.84	0.068
1.8 m	1.01	0.008	1.09	0.008	1.03	0.039	0.87	0.060
3.0 m	0.99	0.007	1.06	0.010	1.01	0.027	0.88	0.049
4.2 m	1.01	0.005	1.06	0.010	1.03	0.018	0.92	0.041
5.4 m	0.99	0.005	1.02	0.008	1.03	0.012	0.92	0.034
Ceiling								
0.6 m	1.05	0.021	1.28	0.044	1.13	0.021	0.83	0.104
1.8 m	1.05	0.019	1.21	0.025	1.11	0.019	0.82	0.077
3.0 m	0.96	0.011	1.02	0.017	1.00	0.011	0.81	0.072
4.2 m	1.02	0.004	1.03	0.025	1.02	0.004	0.91	0.049
5.4 m	1.00	0.005	1.00	0.015	1.00	0.005	0.92	0.033

5.2.3 Measurements of diffuse solar illuminance

The diffuse sky component was measured by eclipsing the sun with the shadow band. Using the shadow band introduces the inherent problem of the submitted correction factor for the part of the sky shaded. The accuracy of the measurments was affected by the following: the obscured, circumsolar sky radiation with high diffuse radiation intensity, non-isotropic sky radiation distribution, the geometry of the ring, interior reflection from the ring due to the material used, adjustments of the ring due to solar declination and the measurement instrument itself.

The correction for the shadow band is often introduced as a simple factor (eq. 5.1 and Table V.3), assuming the atmospheric hemisphere to have isotropic uniform intensity distribution over the sky vault. This assumption does not cope with the nonisotropy of scattered irradiance with its maximum close to the sun, the circumsolar region, the marked change in intensity of the sky and its distibution with different sun elevations, atmospheric turbidities and cloudiness. Several correction methods exist, presenting the correction factor for shadow band based solely on the geometry and assuming the hemisphere to be isotropically diffuse with uniform radiance [Drummond 1956, Robinson 1964, Kipp & Zonen, Littlefair 1989]. The main differences in the algorithms for different isotropic correction factors are the geometry of the shadow band and the solid angle subtended by detector to maintain the intercepted circumsolar part of the sky constant regardless of the declination of the sun [Robinson 1964]. The fraction F of total irradiance (or illuminance) screened off by the shadow band is defined by eq. 5.1 [Kipp & Zonen, Robinson 1964]:

$$F = \frac{X}{T} = \left(\frac{2 \cdot V}{\pi}\right) \cdot \cos\delta\,(\cos\delta \cdot \cos\phi \cdot \sin\omega_s + \sin\delta \cdot \sin\phi \cdot \omega_s) \qquad 5.1$$

where

V	View angle
δ	sun's declination
ϕ	latitude
ω_s	sunset hour angle

As a result of the special ring profile, the view angle varies within ± 2% as a function of the solar declination. The manufacturer claims that the ring profile only causes the error of the applied correction factor to be less than ± 0.5% [Kipp & Zonen], but measurements showed that it varied by ± 4.0% for an overcast sky.

$$Corrected = \left(\frac{1}{1 - F}\right) \cdot Measured \qquad 5.2$$

Table V.3 Monthly correction factors (1/1-F) for Copenhagen.

Month \ Latitude	**latitude 55°**
January	1.02
February	1.03
March	1.06
April	1.09
May	1.12
June	1.14
July	1.13
August	1.11
September	1.07
October	1.04
November	1.02
December	1.01

5.3 Methods of measurements and evaluation criteria

Investigation of three different daylighting systems were conducted from May 1994 to November 1994, using a light shelf, several Venetian blinds and a diffuse curtain. The selected systems are quite diverse in design and are briefly described below (see Chapter 3):

Light shelf: The concept of the light shelves was, as a solid fixture situated either inside or outside of the window to provide shading and redistribution of direct sun and diffuse skylight to the interior. Both the interior and exterior light shelves were tested in several positions: 2.0 m, 1.4 m and 1.1 m (only interior) above floor level. The upper surface of the light shelf was coated with a white diffuse (ρ = 0.70) and a specular reflective surface (ρ = 0.94).

Venetian blinds: The Venetian blinds were located behind the glazing to reflect or redirect light from the slats to the interior and to provide shade in the area near the window. The selected Venetian blinds were highly reflective (small and large), white diffuse (medium), black diffuse (medium) and white/reflective (medium). The blinds were evenly spaced with a width to distance ratio equal to 1.2. The width of the slats varied from: small 16 mm, medium 25 mm and large 35 mm.

Diffuse curtain: The curtain, functioning as a solar shading device, was made of a white semi-translucent material with a shading coefficient of 0.45.

Only one system at a time was evaluated, but the system position or type were sometimes changed during the day (type of Venetian blind, slat angles etc). Although partly clouded skies are the dominant weather condition in Denmark, these conditions are excluded in the investigation due to the existence of infinite numbers of combinations of sky luminance distributions. Therefore each system was only evaluated for two sky conditions, i.e. the overcast sky and the clear sky, with similar solar altitudes and azimuth angles, angles of incidence and profile angles. To provide an accurate performance evaluation relative to the current sky condition, each system is compared to the reference room with an unscreened window, where improvements and disadvantages are evaluated by:

- percentage change in illuminance level between the daylight system relative to the reference room with an unscreened window
- daylight factors
- subjective evalutions (by the author)

The overcast sky conditions gave reproducible conditions, providing a distribution of daylight entering the room almost independent of the solar azimuth angle (Figure 5.8). The main problem was the variations in the sky luminance distribution under which the measurements were made. Variations in the global illuminance depend on the cloud density and type, initial illuminance from the sun and upper sky, transmittance of the clouds, and the inter-reflection between cloud layers and between clouds and the ground [Tregenza 1982]. To compensate for these variation, a criterion for accepting the measurements was defined as the ratio (f_{oc}) between the vertical sky illuminance and global, unobstructed horizontal illuminance. Accepted boundaries for an overcast sky were defined by a ratio interval of vertical to horizontal illuminance between $0.36 \leq f_{oc} \leq 0.44$. The criterion reduced inconsistency in the overcast sky luminance distribution seen by the interior with respect to the exterior hemispheric luminance distribution. However, the measurement discrepancies were most profound if the patch of visible sky luminance seen by the interior was brighter (or darker) than the "invisible" patch of the hemisphere. Figure 5.8 shows the consistency of the measurements, throughout the day, of the relative percentage increase in the interior illuminance levels with an interior reflective light shelf 2.0 m above the floor level (*test room*) compared to the levels with an unscreened window of equal size (*reference room*). The relative percentage increase in interior illuminance levels was defined by eq. 5.3:

$$\%\ \textit{Increase in Illuminance} = \frac{DF_{test\ room}}{DF_{reference\ room}} \cdot 100 \qquad [\%] \qquad 5.3$$

The illumination levels in Figure 5.8, shown as a function of the solar azimuth angle, were measured at the work plane 0.85 m above the floor for an overcast sky condition. The measurements show that interior illuminance levels were almost independent of the solar azimuth. The "missing" data points in Figure 5.8 are points where the ratio of vertical to horizontal illumination was not within the ratio of $0.36 \leq f_{oc} \leq 0.44$. Table V.4 presents the average daylight factors for the interior, reflective light shelf located 2 m above the floor level. The daylight factors show a slightly increased non-uniform luminance distribution when introducing the interior light shelf, caused by the shaded intermediate area. The work plane illuminance level was not increased at the back compared to the reference room.

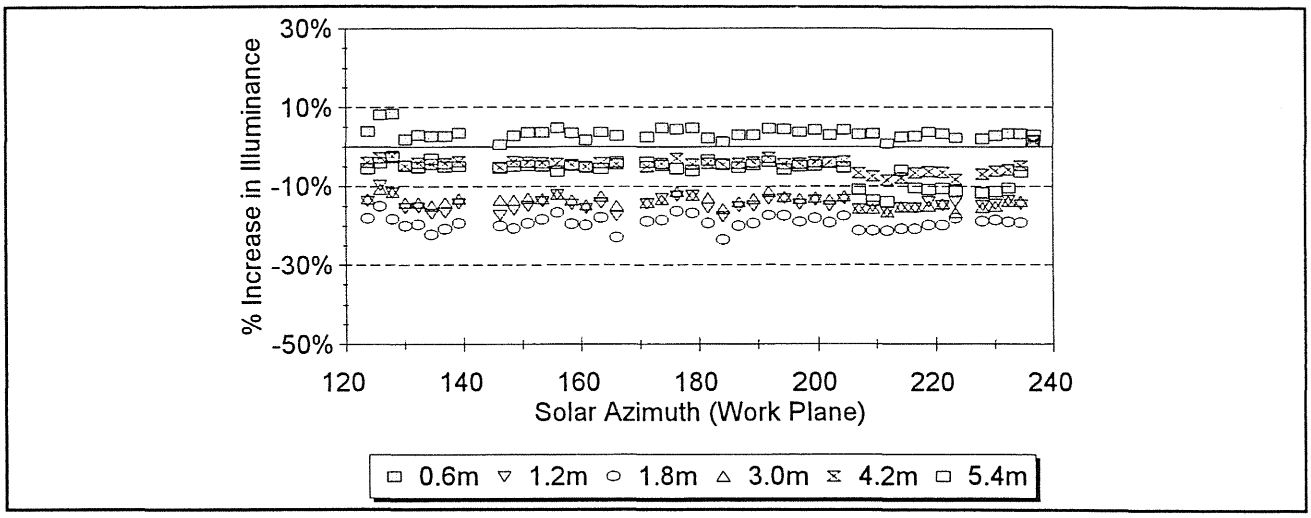


Figure 5.8 Overcast Sky: The percentage change in illuminance level at the Work Plane for an interior reflective light shelf (Pos. 2.0 m) relative to an unscreened window.

Table V.4 Overcast Sky: Min - Max variation of the Daylight Factor in the reference room and in the test room for an interior reflective light shelf (Pos. 2m).

Work Plane		0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
DF [%] Reference Room:	Mean	13.6	7.5	4.1	1.6	0.8	0.5
	STDS	0.9	0.6	0.3	0.2	0.1	0.05
DF [%] Test Room.:	Mean	14.1	6.4	3.3	1.4	0.8	0.4
	STDS	1.0	0.5	0.3	0.1	0.1	0.05

Table V.5 describes the variation of exterior illuminance level, from 08.00-16.00, with the output signal averaged at 1 minute intervals ($\Sigma\ N_{0.36\ \leq\ foc\ \leq\ 0.44}$ = 288 data points). The variation in the exterior measurements throughout the day is described by the min and max value of:

- ratio f_{oc} between vertical sky illuminance and global illuminance ($sky_{vertical}$/global).
- global illuminance (global)
- vertical sky illuminance ($sky_{vertical}$)
- vertical ground reflected illuminance ($ground_{vertical}$)
- diffuse sky illuminance corrected for the shadow ring ($diffuse_{corrected}$)

Table V.5 Overcast Sky: Min - Max variation of the exterior measured illumination.

Exterior Measurement: 8.00 - 16.00 **Interval: 1 min, Σ N = 288**	**Exterior Illuminance [lux]** **Min - Max**
$Sky_{vertical}$/Global	Mean: 0.39 , STDS: 0.22
Global	2170 - 7390
$Sky_{vertical}$	800 - 2950
$Ground_{vertical}$	90 - 300
$Diffuse_{corrected}$	2170 - 7390

The exterior illuminance levels derived from the Danish Test Reference Year (TRY) by the predicted average efficacies for the direct sun, the overcast sky and the clear sky are shown in Figure 5.9 and Figure 5.10. The figures show the cumulative frequencies of daylight, without and with direct sun, respectively, received on an exterior horizontal surface for different occupancy periods. Figure 5.9 shows, for an occupancy period from 08.00-16.00, that the exterior horizontal illuminance is expected to be in the interval between 0-10.000 lux approximately 38% of the period and to exceed 10.000 lux approximately 62% of the period. Using the measured daylight factors of 3.3% at 1.8 m from the window wall (Table V.4) for the interior reflective light shelf, will in the same occupancy period exceed an illuminance level of 330 lux approximately 62% of the period. In the reference room with a daylight factor of 4.1% at 1.8 m, this will cause the illuminance level of 410 lux to be exceeded 62% of the period.

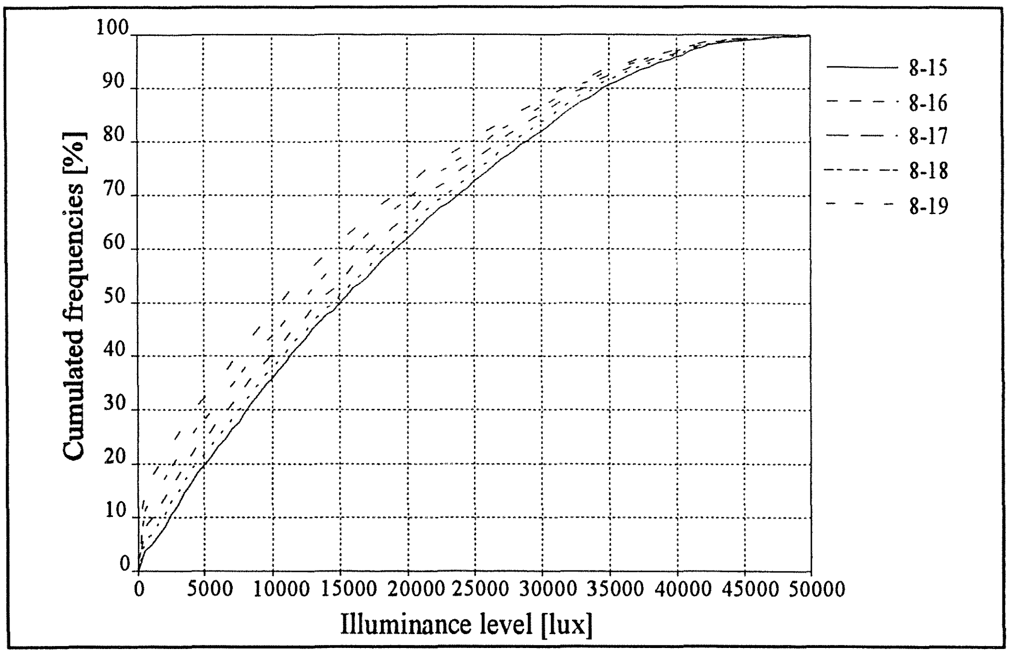


Figure 5.9 Cumulative frequencies in percent of selected occupancy periods of daylight on an exterior horizontal surface in Denmark (direct sun is excluded).

Measurements for the clear sky with direct sun were mainly conducted with the solar azimuth angle perpendicular to the building facade. Some measurements were also carried out by equal time separation between morning and afternoon, where the resulting interior illuminance levels are the mean value of the two measured illuminances. However, difficulties in the monitoring procedures occurred in situations with direct and/or reflected sunlight in the interior, since high illuminance values (Table V.1) resulted in a state of saturation of the detectors. This produced indefinite evaluation of the illuminance level in the front half of the room, but it showed the system's reduced ability to shade penetration of direct sun. Additionally, the asymmetrical window location in the facade caused increased sensitivity of the room configuration due to the difference in the distance to nearby adjacent side walls in the morning and afternoon (see Table V.2).

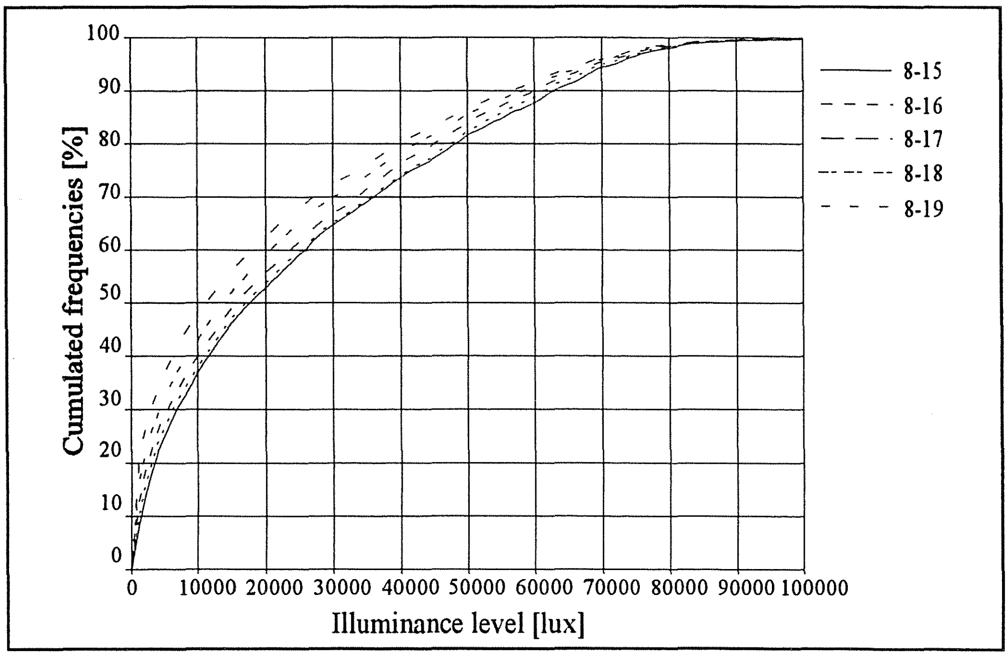


Figure 5.10 Cumulative frequencies in percent of selected occupancy periods of daylight on an exterior vertical surface 15° west of due south in Denmark (direct sun is included).

The interior illuminance levels (in lux) were adjusted relative to a fixed, exterior vertical sky illuminance at the facade (70.000 lux). The adjustments were conducted to reach comparable interior light levels, since the exterior illuminance level varied during the time of measurements. Figure 5.10 shows the cumulative frequencies of daylight, with direct sun, received on the exterior vertical surface 15 degrees west of due south for the same occupancy periods described earlier. Taking the direct sun radiation into account, the illuminance level of 70.000 lux is exceeded in approximately 5% of the occupancy period.

The profile angle (Φ) is the projection of the solar altitude angle on a vertical plane perpendicular to the window plane. The solar altitude angle γ_s (i.e. $\angle$ BAC), and the profile angle Φ (i.e. $\angle$ DEF), for a surface are illustrated in Figure 5.11, Figure A.6. The solar altitude and profile angle are the same when the solar azimuth angle is perpendicular to the facade. The sun's profile angle from March 22nd to September 21st is above 34°, while the profile angle is between 0°-34° in the rest of the year. The specular light shelf will reflect a bright sun spot on the ceiling at a distance from the window wall determined by the profile angle Φ. Due to the variations of the profile angle in the summer (March 22nd to September 21st) and in the winter, a south facing light shelf will cause the sun spot to obtain its greatest penetration when the sun elevation reaches its maximum, while this is reversed in the winter. The spring and autumn equinoxes for a south facing facade will cause the bright spot of penetrated sunlight at the floor to be unchanged during the time when sunlight falls on the window. The profile angle can be found by eq. 5.4:

$$\tan\Phi = \frac{\tan\gamma_s}{\cos(\alpha_s - \alpha_k)} \tag{5.4}$$

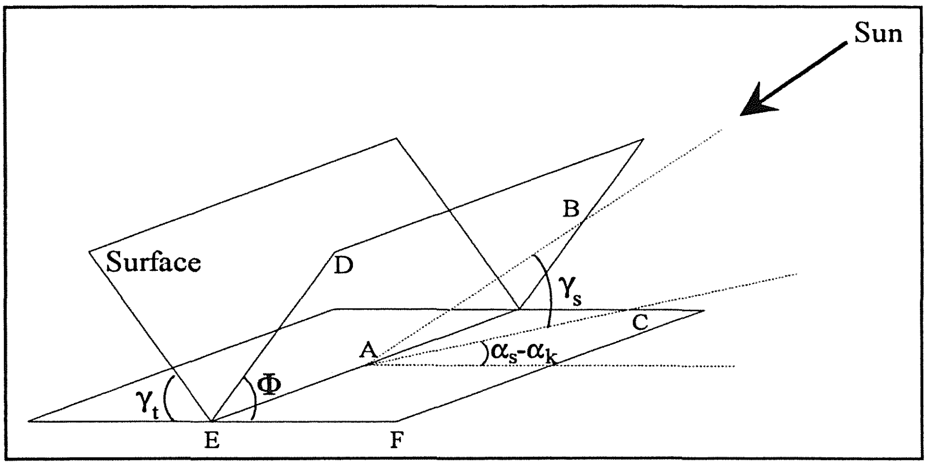


Figure 5.11 The solar altitude angle γ_s (i.e. $\angle$ BAC), and the profile angle Φ (i.e. $\angle$ DEF), for the surface.

6. Measurements of Three Selected Daylight Sidelighting Systems

The investigation of the performance of three different daylighting, sidelighting techniques was conducted in two sparsely furnished mock-up offices with fixed reflectances of the floor, ceiling and side walls. The offices were orientated 15 degrees west of due south with room dimensions: 3.2 m wide, 6.75 m deep, and 3.1 m high. In the south facade, two windows of equal size with a glazing area of 1.54 m high and 2.16 m wide (window-sill height 1.1 m), were asymmetrically located in the facade. The measurments were conducted from May to November 1994 for: 1) interior and exterior light shelves, 2) several Venetian blinds, and 3) a diffuse curtain (see Chapter 3). The assessments were carried out with the intention of acquiring a profound understanding of the behaviour of natural light in the interior environment. The systems were evaluated by the qualitative and quantitative consequences of introducing "new" technologies, aiming at improvement of the utilisation of daylight. The investigations paid special attention to the systems' ability to enhance daylight penetration, which may increase the possibility of replacing artificial lighting with daylight in the intermediate area and at back of the room. However, since the mock-up offices lack the reality of a normal furnished room, the transfer of the results to a real situation may change the evaluation of the performance significantly. The interior quantities and qualities were determined by:

- monitoring illuminances on the work plane and on the ceiling surface.
- comparison of daylight distribution for the selected daylight system and the reference room.
- evaluation of visual "comfort" by measurements of the luminances in the room and the window surface, in order to calculate the Cornell glare-index (DGI) and luminance ratios.
- evaluation of visual "comfort" by subjective assessments of the interior environment (by the author).

6.1 Performance of interior and exterior light shelves

All experimental assessments of the interior and the exterior light shelf were conducted from May to October 1994. The light shelf was a "simple" solid fixture with the following geometrical dimensions: 0.5 m deep and 2.16 m wide, equal to the width of the window. It separated the window function into a "daylight window" and a view window. Both a matt white surface (ρ = 0.7, diffuse reflection) and a highly reflective aluminium surface (ρ = 0.94, specular reflection) were tested. The light shelf was located both inside and outside of the window pane, shading the window perimeter area while redistributing direct and diffuse skylight to the ceiling.

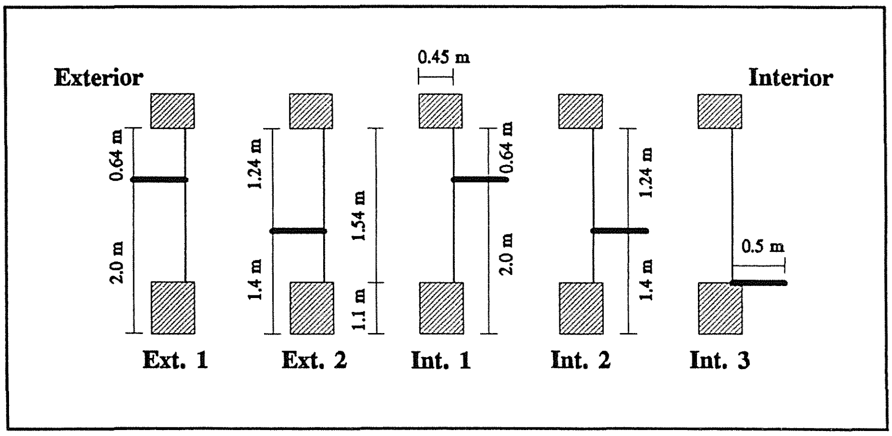


Figure 6.1 A principle illustration of location and geometrical dimension of the investigated light shelves.

Both the interior and the exterior light shelf were tested in several positions (see Figure 6.1); interior and exterior 2.0 m (Int. 1 & Ext. 1), interior and exterior 1.4 m (Int. 2 & Ext. 2) and interior 1.1 m (Int. 3) above the interior floor level. Variations in the light shelf position were mainly dictated by the extended exterior overhang (0.45 m), the downward tilted window-sill and the exterior vertical side fin (0.4 m) to the right of the daylight laboratory, viewed from the inside. A light shelf is usually positioned 1.9 m to 2.1 m above floor level, determined by the room configuration and eye level of a standing person, to avoid reflected glare. However, in this case the low positions were assessed with the intention of exploring the physical benefits of increased reflected light to the ceiling, regardless of the unbearable visual distractions in the interior. Visual discomfort can be reduced if the light shelf reduces the brightness of the window area and modifies the contrast between the darkest and brightest parts of the room. This again will depend on the light shelf's geometry, material properties, position and its ability to reduce exposure to the visible sky.

6.1.1 Interior light shelf: Overcast Sky

The measurements of the interior light shelf were conducted in three different interior positions (see Figure 6.1) using both the white diffuse and the highly reflective surface coating. The diffuse light shelf obeys the law of Lambertian reflection with reduced or no directional "control" while the reflective light shelf causes directional reflection of the incident light. The concept of the interior light shelf is: 1) to redistribute the light of the visible patch of sky subtended by the light shelf to the interior, and 2) to shade the front end of the room.

Interior light shelf (Int. 1): Position 1 (2 m)

The interior light shelf, 2 m above the floor level, reduced the relative work plane illuminance level compared to the reference room with an unscreened window of equal size. Figure 6.2 shows the profile angle (34°) as the fraction of the sky fully visible from the light shelf. The position of the light shelf shows limited or no exposure to sky radiation from the high luminance areas near the zenith due to the exterior overhang (0.45 m).

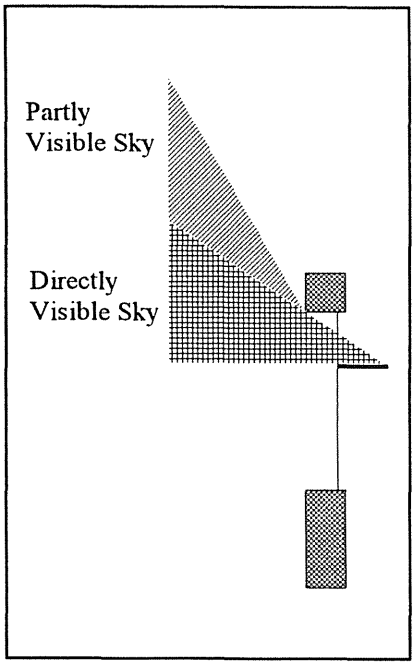


Figure 6.2 Int. (1): The profile angle for an interior light shelf of the visible and partly visible sky.

The *diffuse light shelf* reduced the work plane illuminance level by 15-25% compared to the reference room (Figure 6.5). The reductions were highest (20-25%) in the intermediate area (1.2-3.0 m) and lowest (15%) at the back (4.2-5.4 m). Interpretation of these results, with the interior light shelf, showed a slightly increased non-uniform luminance distribution compared to the reference room. Table V.1 and Table V.3 show the measured average daylight factors on the work plane. For example, an overcast sky with an exterior horizontal illuminance level of 10000 lux causes the work plane illuminance level at 1.8 m to be reduced from 390 lux (reference room) to 290 lux (diffuse light shelf), while at the back, the relative reductions may be deceiving, since they are results of the differences between small illuminance levels. Here, the the example shows a reduction of the absolute illuminance level from 40 lux (reference room) to 30 lux (diffuse light shelf). These measured differences at 5.4 m from the window wall are practically negligible

The *reflective light shelf* reduced the work plane illuminance level from 14-19% in the intermediate zone (1.2-3.0 m), while the reduction was 5% at the back (Figure 6.7). The discrepancies at the window wall (0.6 m) between the diffuse (-3%) and reflective light shelf (+3%), can only be explained as the result of increased inter-reflection from the adjacent sidewalls caused by the reflective light shelf.

Measurements on the ceiling surface showed the differences between the diffuse and the reflective light shelf. The diffuse light shelf increased the illuminance level by 27% at 0.6 m, while it was reduced by roughly 10% at 3-5.4 m (Figure 6.6). With the reflective light shelf, the illuminance level was boosted by 94% at 1.8 m, but reduced by 10% at 0.6 m (Figure 6.8). The illuminance level in the remaining part of the room was increased by 4-13%, least at the back.

Interior light shelf (Int. 2): Position 2 (1.4 m)
Figure 6.3 shows an increased profile angle from 34° to 53°, when the light shelf is moved to the lower position. The light shelf at 1.4 m above the floor level also reduces the influence of the exterior overhang, while increasing the exposure to the sky radiation from the high luminance areas near zenith.

The *diffuse light shelf* reduced the relative work plane illuminance level at 1.8-5.4 m by 3-8% (Figure 6.5). The severe reductions in the window perimeter area can be ignored due to the unnatural position of the light shelf shading the window perimeter (0.6-1.2 m).

The *reflective light shelf* increased the work plane illuminance level at 1.8-5.4 m by 0-16%, compared to reference room (Figure 6.7). The improved illuminance level between the two positions is mainly the result of increasing the height of the "daylighting window" from 0.64 m (Int. 1) to 1.24 m. (Int. 2), reducing the effect of the exterior overhang.

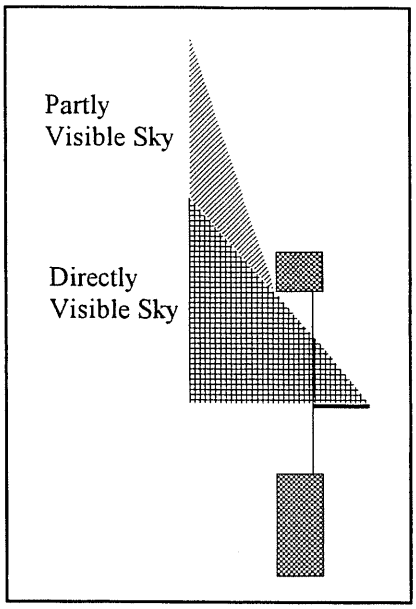


Figure 6.3 Int. (2): The profile angle for an interior light shelf of the visible and partly visible sky.

The light shelf in the lower position increased the penetration of the reflected light deeper into the interior. This is illustrated by the diffuse light shelf increasing the illuminance level on the ceiling by 68% (0.6 m) and 23% (1.8 m) (Figure 6.6). The reflective light shelf caused a more extreme variation, increasing the illuminance level by 192% at 1.8 m (Figure 6.8). Compared to the reflective light shelf at 2 m, the relative illuminance level was improved by almost 100% at 1.8m and 25% at 0.6 m.

Interior light shelf (Int. 3): Position 3 (1.1 m)
Moving the light shelf to the window-sill height (1.1 m), gives the the maximum profile angle (58°) (Figure 6.4).

The illuminance level at the workplane throughout the interior was higher than the reference room, even with the *diffuse light shelf* (0-2%) (Figure 6.5). The *reflective light shelf* increased the illuminance level by 12-22% (Figure 6.7).

Measurements on the ceiling surface for the diffuse light shelf at the window-sill showed a lower illuminance level at 0.6 m (47%), but this was allegedly caused by a more directional diffuse reflection, affecting the transition between the two detectors at 0.6 m and 1.8 m (Figure 6.6). The reflective light shelf did not increase the illuminance level in the window perimeter (0.6-1.2 m), but improved the illuminance level compared to the reflective light shelf at 1.4 m by 10-15% in the rest of the room (3-5.4 m) (Figure 6.8).

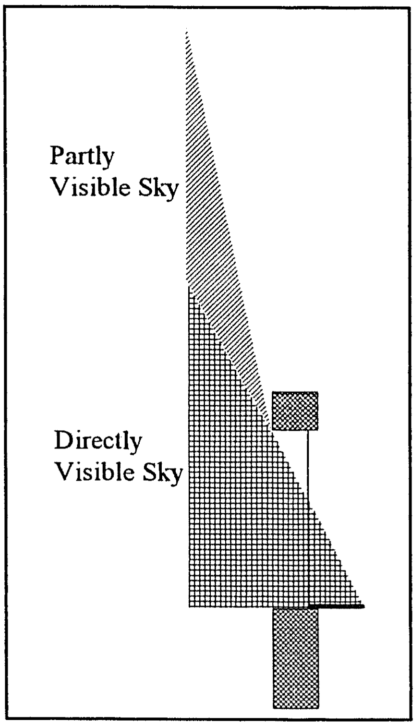


Figure 6.4 Int. (3): The profile angle for an interior light shelf of the visible and partly visible sky.

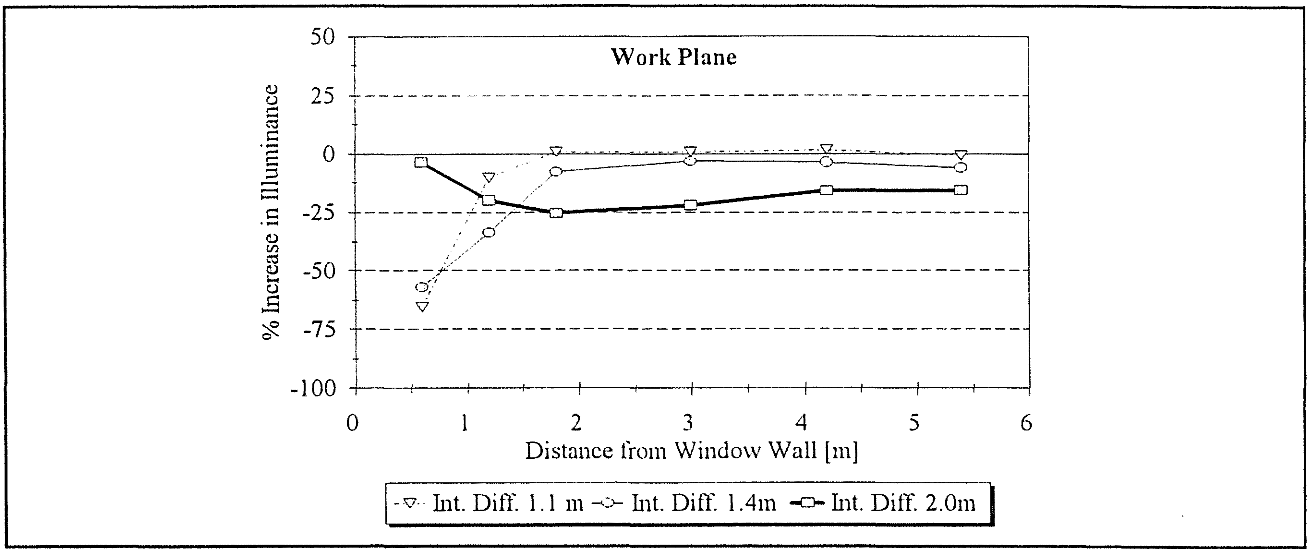


Figure 6.5 Overcast Sky: The percentage change in illuminance level on the Work Plane for an interior diffuse light shelf relative to the reference room.

Table V.1 Average Daylight Factors [%] on the Work Plane for a diffuse interior light shelf and the reference room.

Work Plane	**0.6 m**	**1.2 m**	**1.8 m**	**3.0m**	**4.2 m**	**5.4 m**
Reference Room	14.1±0.2	7.4±0.1	3.9	1.5	0.7	0.4
LHD Pos. 1.1 m	4.9	6.7	4.0	1.5	0.8	0.4
LHD Pos. 1.4 m	6.0	4.9	3.6	1.4	0.7	0.4
LHD Pos. 2.0 m	13.8	6.0	2.9	1.1	0.6	0.3

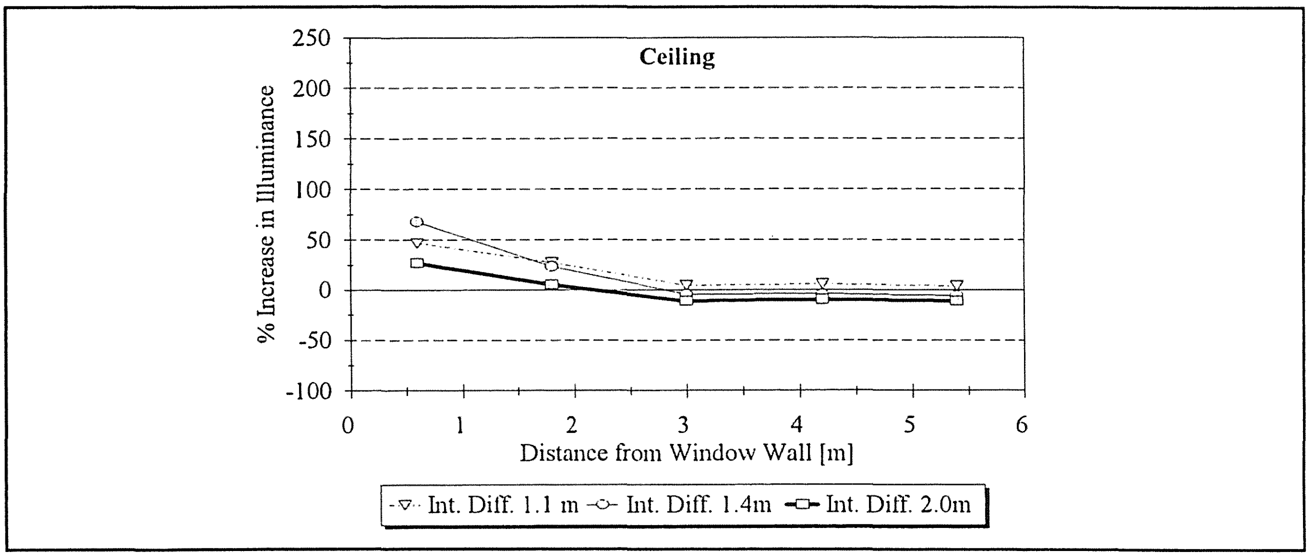


Figure 6.6 Overcast Sky: The percentage change in illuminance level on the Ceiling for an interior diffuse light shelf relative to the reference room.

Table V.2 Average Daylight Factors [%] on the Ceiling for a diffuse interior light shelf and the reference room.

Ceiling	**0.6 m**	**1.8 m**	**3.0 m**	**4.2 m**	**5.4 m**
Reference Room	1.9±0.2	1.2±0.1	0.7±0.1	0.4	0.2
LHD Pos. 1.1 m	3.1	1.7	0.8	0.4	0.3
LHD Pos. 1.4 m	3.0	1.4	0.6	0.4	0.2
LHD Pos. 2.0 m	2.1	1.1	0.6	0.3	0.2

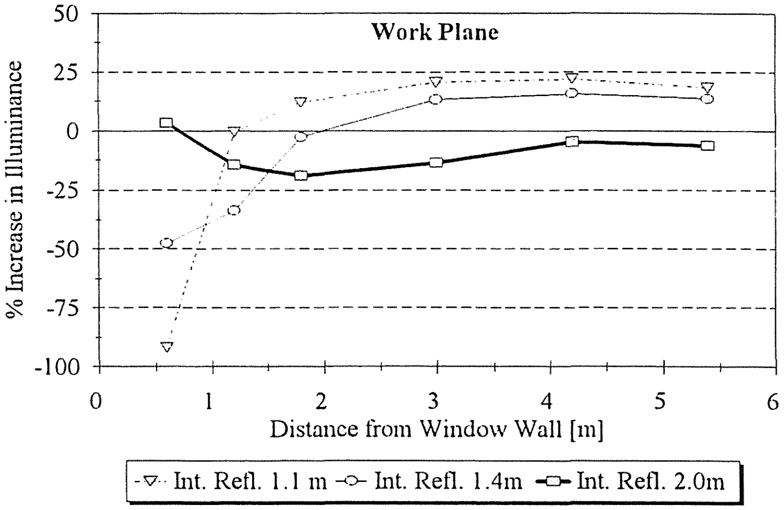


Figure 6.7 Overcast Sky: The percentage change in illuminance level on the Work Plane for an interior reflective light shelf relative to the reference room.

Table V.3 Average Daylight Factors [%] on the Work Plane for a reflective interior light shelf and the reference room.

Work Plane	**0.6 m**	**1.2 m**	**1.8 m**	**3.0 m**	**4.2 m**	**5.4 m**
Reference Room	13.8±0.2	7.6±0.1	4.1	1.6	0.8	0.5
LHR Pos. 1.1 m	1.1	7.5	4.6	1.9	1.0	0.5
LHR Pos. 1.4 m	7.3	5.1	4.1	1.8	1.0	0.5
LHR Pos. 2.0 m	14.1	6.4	3.3	1.4	0.8	0.4

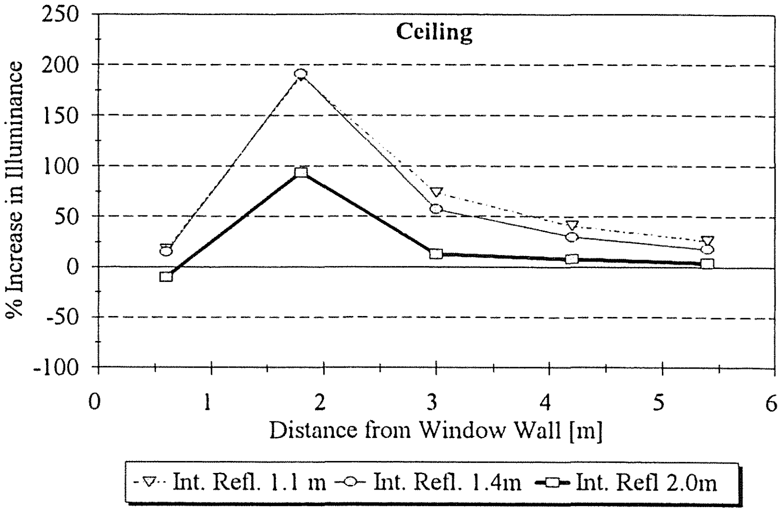


Figure 6.8 Overcast Sky: The percentage change in illuminance level on the Ceiling for an interior reflective light shelf relative to the reference room.

Table V.4 Average Daylight Factors [%] on the Ceiling for a reflective interior light shelf and the reference room.

Ceiling	**0.6 m**	**1.8 m**	**3.0 m**	**4.2 m**	**5.4 m**
Reference Room	1.6±0.1	1.1	0.7	0.4	0.2
LHR Pos. 1.1 m	2.0	3.1	1.1	0.5	0.3
LHR Pos. 1.4 m	1.7	3.0	1.0	0.5	0.3
LHR Pos. 2.0 m	1.4	2.1	0.7	0.4	0.3

6.1.2 Exterior light shelf: Overcast Sky

The measurements of the exterior light shelf were conducted in two different positions (see Figure 6.1) using both the white diffuse and the highly reflective surface coating. Moving the light shelf to the exterior merely creates a parallel movement of the room's shaded and reflected area towards the window facade. Compared to the interior light shelf, the exterior light shelf receives more sky radiation from the high luminance area near zenith.

Exterior light shelf (Ext. 1): Position 1 (2 m)

The exterior light shelf 2 m above the floor level reduced the work plane illuminance level compared to the reference room. Figure 6.9 shows an increased profile angle from 34° (interior) to 55°, reducing the influence of the exterior overhang (0.45 m)

The *diffuse light shelf* reduced the relative work plane illuminance level by 12-45% compared to the reference room (Figure 6.11). The shaded area moved from the intermediate area to the window perimeter, reducing the illuminance level on the work plane by 45% at 0.6 m and 31% at 1.2 m. The illuminance level in the rest of the room (1.8-5.4 m) was reduced by 12-16%.

The *reflective light shelf* reduced the illuminance level at 3-5.4 m by 7-12%, while the reduction at the window perimeter was almost the same as for the diffuse light shelf (Figure 6.13).

Measurements on the ceiling surface are shown in Figure 6.12 and Figure 6.14. The diffuse light shelf increased the illuminance level by 76% at 0.6 m, while it was reduced in the remaining part of the room (14% at 3-5.4 m) (Figure 6.12). The reflective light shelf boosted the illuminance level at 0.6 m by 230%, while it was reduced by 7-12% in the remaing part of the room (3-5.4 m) (Figure 6.14).

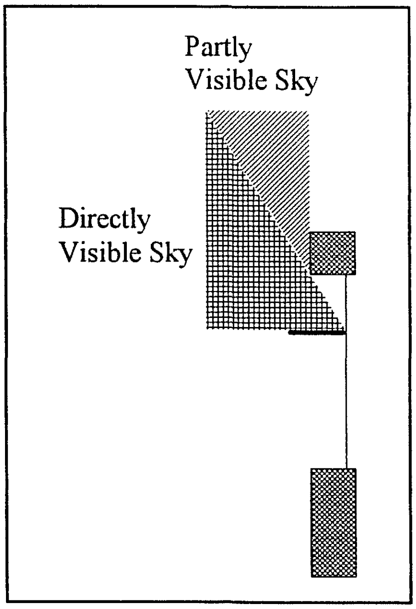


Figure 6.9 Ext. (1): The profile angle for an exterior light shelf of the visible and partly visible sky.

Exterior light shelf (Ext. 2): Position 2 (1.4 m)

Figure 6.10 shows that the profile angle was increased from 55° to 70° for the light shelf at 1.4 m above the floor level, causing a reduced shading of the window perimeter.

The *diffuse light shelf* shows a work plane illuminance almost identical to that in the reference room (Figure 6.11). The illuminance level was increased by 2% in the intermediate area (1.8-3.0 m) and slightly reduced at the back by 3% (4.2-5.4 m).

The *reflective light shelf* increased the illuminance level by 3-10%, highest at 1.8-4.2 m (Figure 6.13).

The diffuse light shelf slightly increased the illuminance level on the ceiling by 86% at 0.6 m and 36% at 1.8 m (Figure 6.12). There were negligible differences in the remaing part of the room between the exterior diffuse light shelf and the reference room. The reflective light shelf caused no improvement between the two exterior positions at 0.6 m, since both increased the illuminance level by 230% (Figure 6.14). The illuminance level at 3-5.4 m was increased by 3-19%, highest in the middle of the room.

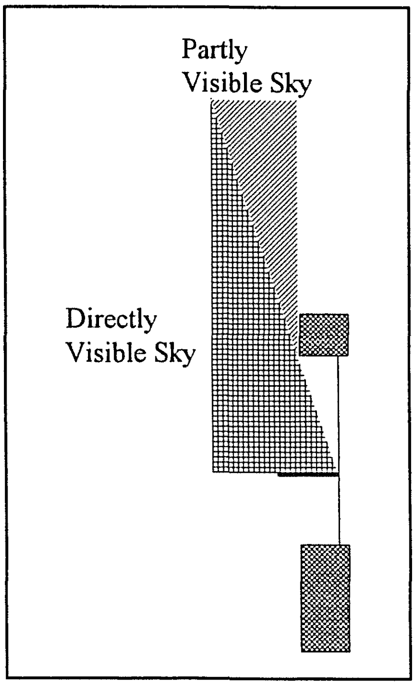


Figure 6.10 Ext. (2): The profile angle for an interior light shelf of the visible and partly visible sky.

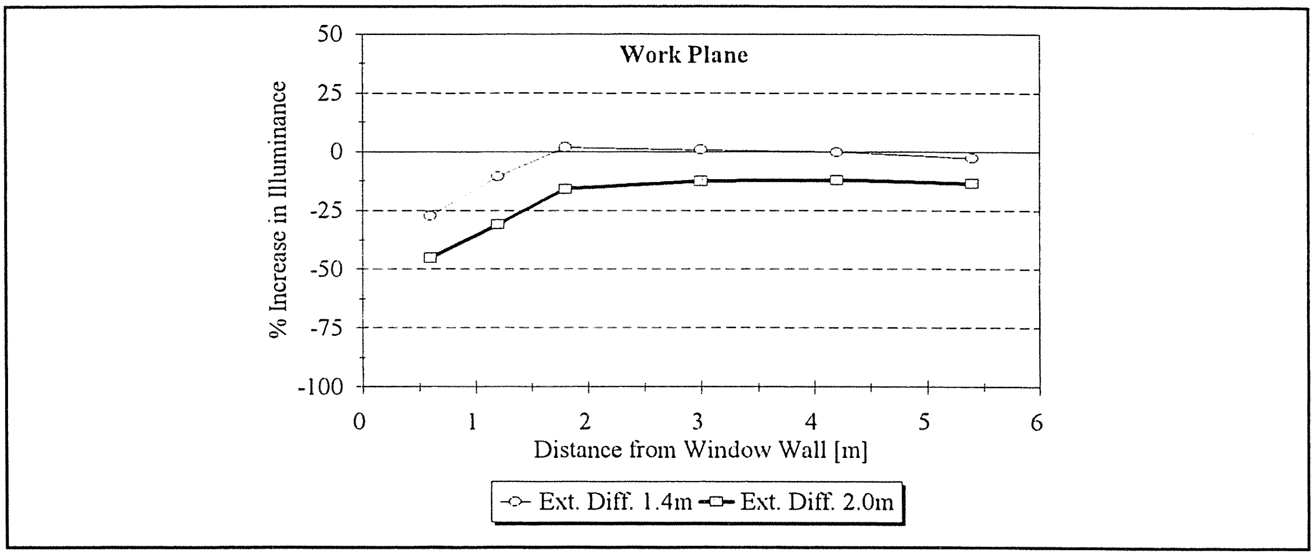


Figure 6.11 Overcast Sky: The percentage change in illuminance level on the Work Plane for an exterior diffuse light shelf relative to the reference room.

Table V.5 Average Daylight Factors [%] on the Work Plane for a diffuse exterior light shelf and the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	13.6±0.1	7.2	3.8	1.4	0.7	0.4
LHD Pos. 1.4 m	9.8	6.4	3.9	1.5	0.7	0.4
LHD Pos. 2.0 m	7.5	5.0	3.2	1.2	0.6	0.4

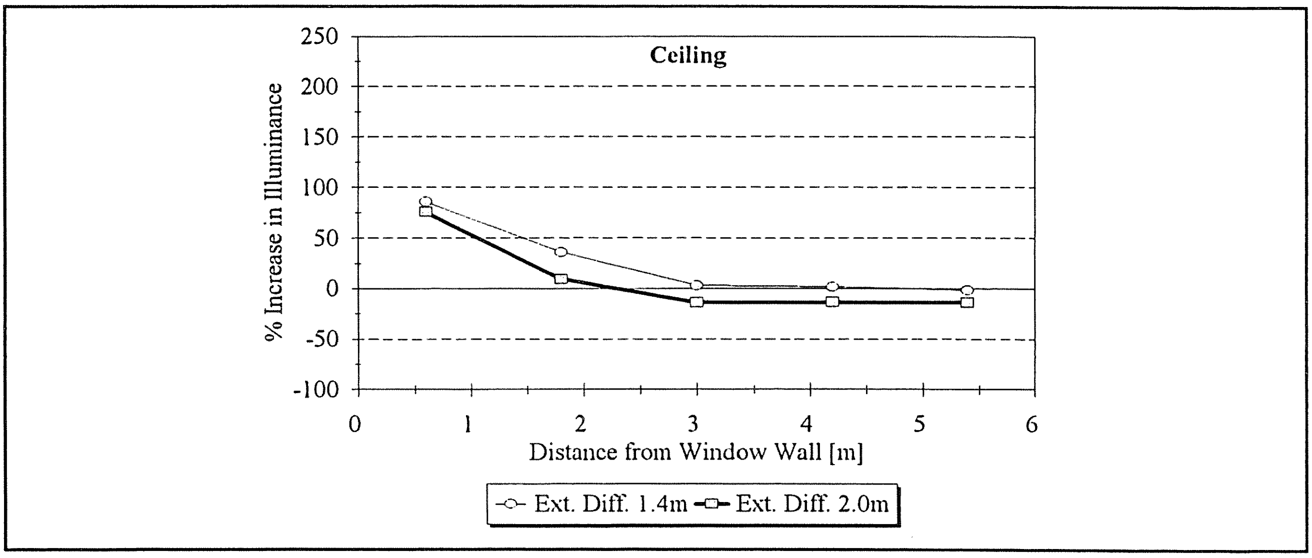


Figure 6.12 Overcast Sky: The percentage change in illuminance level on the Ceiling for an exterior diffuse light shelf relative to the reference room.

Table V.6 Average Daylight Factors [%] on the Ceiling for a diffuse exterior light shelf and the reference room.

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	1.6	1.0	0.6	0.4	0.2
LHD Pos. 1.4 m	3.0	1.4	0.6	0.4	0.2
LHD Pos. 2.0 m	2.9	1.1	0.5	0.3	0.2

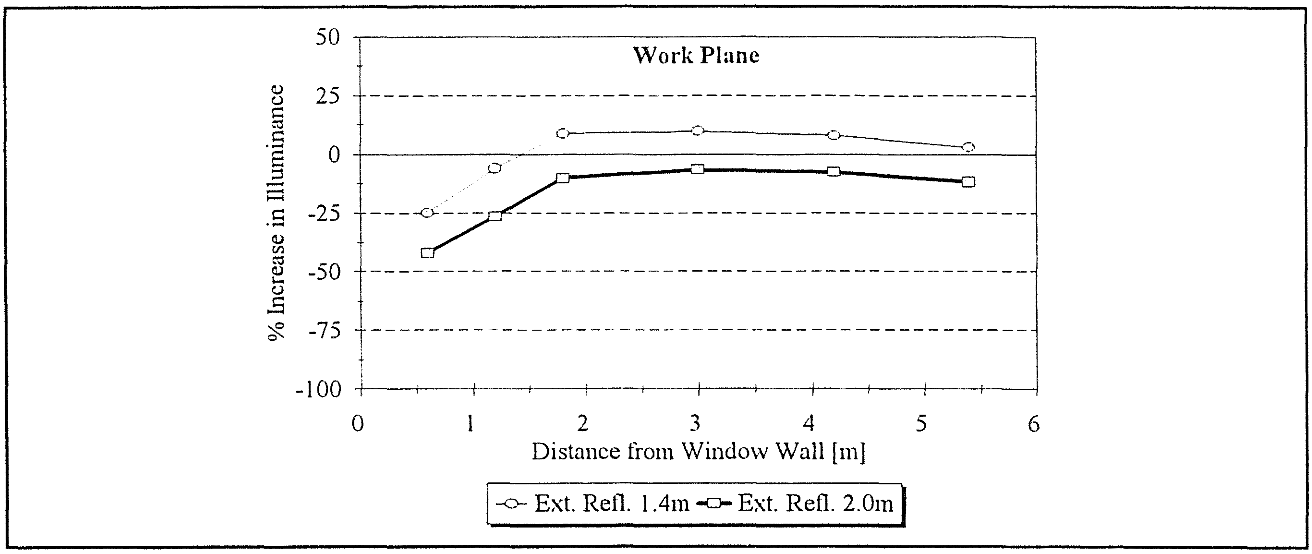


Figure 6.13 Overcast Sky: The percentage change in illuminance level on the Work Plane for an exterior reflective light shelf relative to the reference room.

Table V.7 Average Daylight Factors [%] on the Work Plane for a reflective exterior light shelf and the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	14.1±0.2	7.6±0.1	4.1	1.6	0.8	0.5
LHR Pos. 1.4 m	10.7	7.2	4.5	1.7	0.9	0.5
LHR Pos. 2.0 m	8.1	5.5	3.6	1.4	0.7	0.4

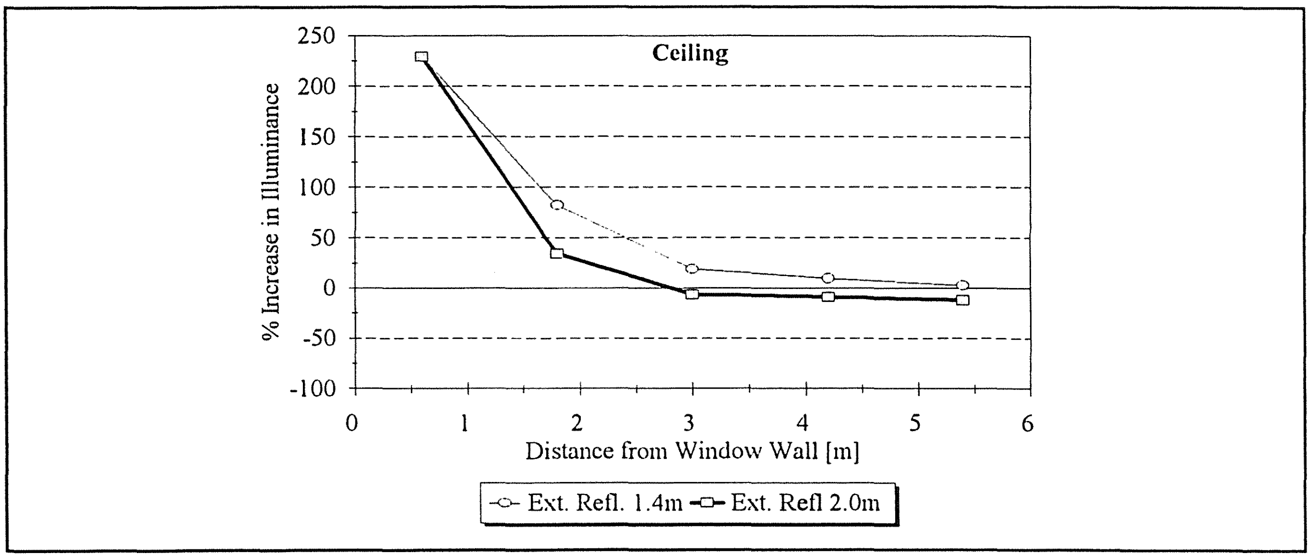


Figure 6.14 Overcast Sky: The percentage change in illuminance level on the Ceiling for an exterior reflective light shelf relative to the reference room.

Table V.8 Average Daylight Factors [%] on the Ceiling for a reflective exterior light shelf and the reference room.

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	1.7	1.1	0.7	0.4	0.2
LHR Pos. 1.4 m	5.6	2.0	0.8	0.4	0.3
LHR Pos. 2.0 m	5.4	1.4	0.6	0.4	0.2

6.1.3 Comparison of the interior and the exterior light shelf (2 m): Overcast Sky

The exterior light shelf reduced work plane illuminance level at the window perimeter, satisfying one of the intentions of the light shelf. The increased profile angle for the exterior light shelf caused the interior illuminance level to be increased compared to the interior light shelf, although it did not increase the illuminance level at the back.

Figure 6.15 shows the daylight factors on the work plane for the interior and the exterior reflective light shelf (Table V.9). The interior light shelf caused a slightly increased, non-uniform luminance distribution compared to the reference room, due to the shaded intermediate area. The exterior light shelf produced a more uniform distribution by the reduced difference between the window perimeter and at the back of the room. The measurements on the work plane show that the usually recommended daylight factor of 2% occurs at a distance of approximately 2.5 m from the window.

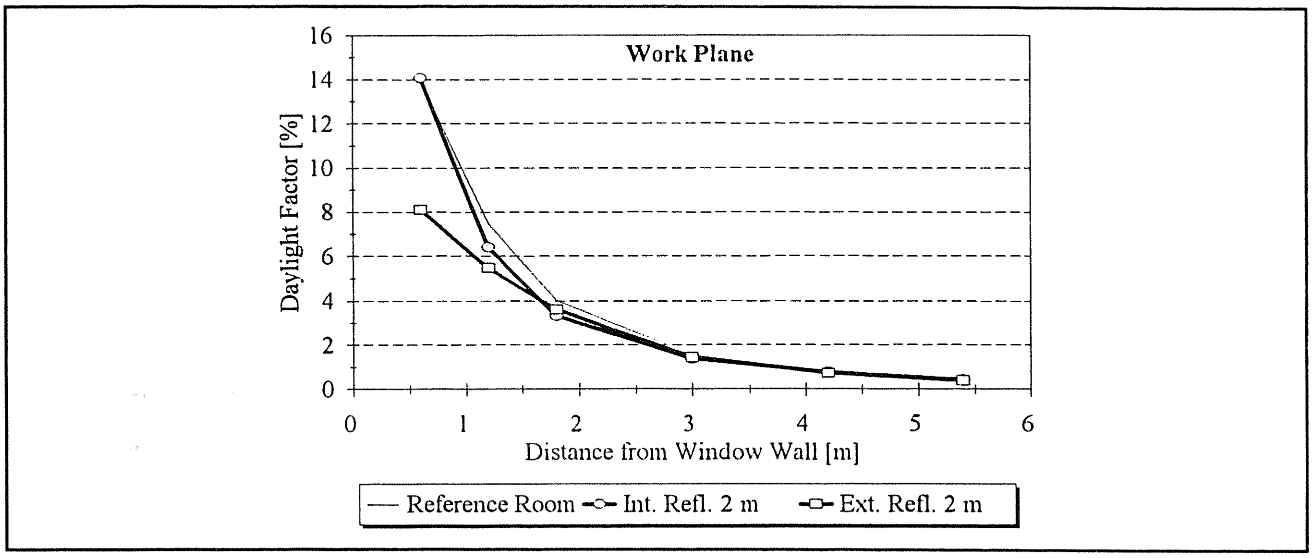


Figure 6.15 Overcast Sky: The daylight factor [%] on the Work Plane for an interior and exterior reflective light shelf (2m) compared to the reference room.

Table V.9 Average Daylight Factors [%] on the Work Plane for an interior and exterior reflective light shelf at 2 m above the floor level compared with the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	13.8±0.2	7.5	3.9±0.1	1.5±0.1	0.8	0.5
LHR Pos. 2.0 m: Exterior	8.1	5.5	3.6	1.4	0.7	0.4
LHR Pos. 2.0 m: Interior	14.1	6.4	3.3	1.4	0.8	0.4

The increased profile angle affected the measurement at the window perimeter on the ceiling, where the exterior diffuse light shelf, compared to the interior, increased the relative illuminance level by approximately 50% at 0.6 m while the increase was less profound at 1.8 m (4%). There were no real differences in the remaining part of the room (3-5.4 m). The differences were more significant with the reflective surface since the exterior light shelf increased the illuminance level by 240% at 0.6 m relative to the interior. However, it was the opposite at 1.8 m, since the illuminance level for the interior reflective light shelf here was increased by 60% relative to the exterior. The remaing part of the room showed similar tendencies as with the diffuse light shelf. The differences between the interior and the exterior are merely a result of the parallel movement of the reflected incident light moving towards the window, producing a lower illuminance level on the ceiling in the central part of the room.

6.1.4 Interior light shelf: Clear Sky with direct sun

Measurements with the diffuse and the reflective light shelf for a clear sky with direct sun were mainly conducted in May and October 1994 for a solar azimuth angle perpendicular to the window facade. Some measurements were also carried out by equal time separation from "noon" in the morning and the afternoon, where the resulting interior illuminance levels are the mean value of the two measured illuminances. This will reduce the effect of the asymmetrical window displacement and the influence of interior inter-reflection from the nearby adjacent side walls as a function of time of day. The lack of measurements with the diffuse light shelf was a consequence of coincidental recalibrations of the exterior detectors, which limited fully documented, clear sky measurements of the diffuse light shelf in May. The lack of measurements in October was a result of incomparable clear sky conditions and the consequence of the daylight laboratory being "closed-down" at the beginning of November.

To achieve comparable interior illuminance levels (lux), the measured values were adjusted relative to a fixed reference value of the exterior vertical sky illuminance on the facade of 70.000 lux. Table V.10 and Table V.12 show the adjusted interior illuminance levels on the work plane for the interior diffuse and the reflective light shelf, respectively. Inconsistency in the measurements shows that the detectors are either in direct sunlight or beyond maximum output voltage of the detectors, causing the detectors to be in a state of saturation. High solar altitudes (May), with a profile angle higher than 34° (Figure 6.2), excluded the interior light shelf at 2 m as a shading device. This caused the detectors at the window perimeter to be in direct sun (0.6 m > 20000 lux and 1.2 m > 4000 lux) (Table V.10). Low solar altitudes (October), with the light shelf at 2 m, caused the sun to penetrate both the window perimeter and the intermediate area (1.8 m > 4000 lux), through the space between the light shelf and the ceiling surface (Table V.12). This shows the interior light shelf's lack of ability to shade the front half of the room and this results in a need for additional shading devices. Figure 6.16 and Figure 6.18 show the relative work plane illuminance level compared to the reference room with an unscreened window of equal size, where detectors in a state of saturation are not shown.

In May, the *diffuse light shelf* at 2 m reduced the work plane illuminance level at 1.8-5.4 m from the window by 9-17%, compared to the reference room (Figure 6.16). The reductions were highest (13-17%) in the intermediate area (1.8-3.0 m) and lowest (9-10%) at the back (4.2-5.4 m). Moving the diffuse light shelf to the window-sill height (October) reduced the work plane illuminance level by 0-10% at the back. Caution should be taken since the measurements with the light shelf at 1.1 m were carried out in the afternoon and are assigned to the largest differences between the daylight laboratory and the reference room (see chapter 5). However, the presence of these problems has less effect on the interior illuminance levels in the daylight laboratory, since a perfectly diffuse surface is independent of the light's angle of incidence.

In October, the *reflective light shelf* at 2 m increased the illuminance level by 35% at 4.2 m and 14% at 5.4 m, compared to the reference room (Figure 6.18). Moving the reflective light shelf to the lower positions caused an increased work plane illuminance level at the back (4.2-5.4 m) by 52-71%, highest at 4.2 m. Comparison with the reflective light shelf at 2 m shows that the illuminance level was increased at the back (5.4 m) by 38% and 56% for the light shelf at 1.4 m and 1.1 m, respectively (October). Table V.12 shows that the reflective light shelf at the lower positions caused the absolute illuminance levels at the back in October to be enhanced by almost 100%, compared to the equal measurements in May. With the reflective light shelf at 1.4 m, the increase of relative work plane illuminance level at the back was more moderate but still significant. The illuminance level at the back was increased from 35% in May to 52% in October. However, this was not the case with the reflective light shelf at 1.1 m, since the relative increase of the illuminance level at the back was reduced from 90% in May to 70% in October.

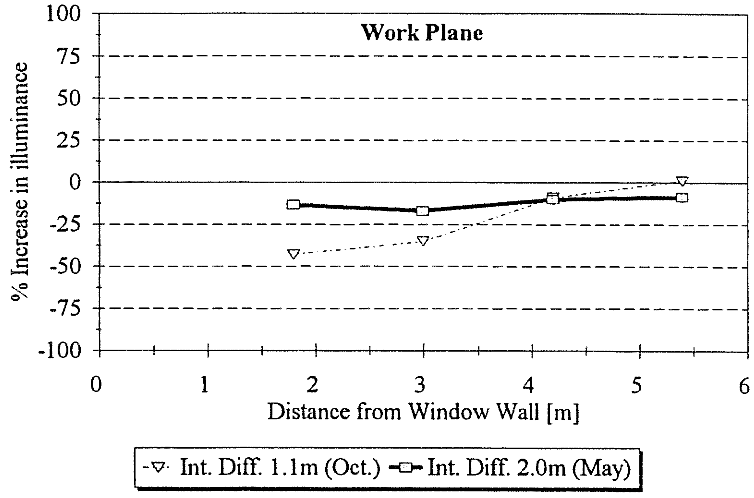


Figure 6.16 Direct Sun: The percentage change in illuminance level on the Work Plane for an interior diffuse light shelf relative to the reference room.

Table V.10 Average Illuminance level [lux] on the Work Plane for an interior diffuse light shelf adjusted to exterior vertical sky illuminance (70.000 lux).

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
LHD Pos. 1.1 m [lux] - Oct.	1290	2060	1870	1340	900	530
LHD Pos. 2.0 m [lux] - May	> 20000	> 4000	2440	1110	670	390

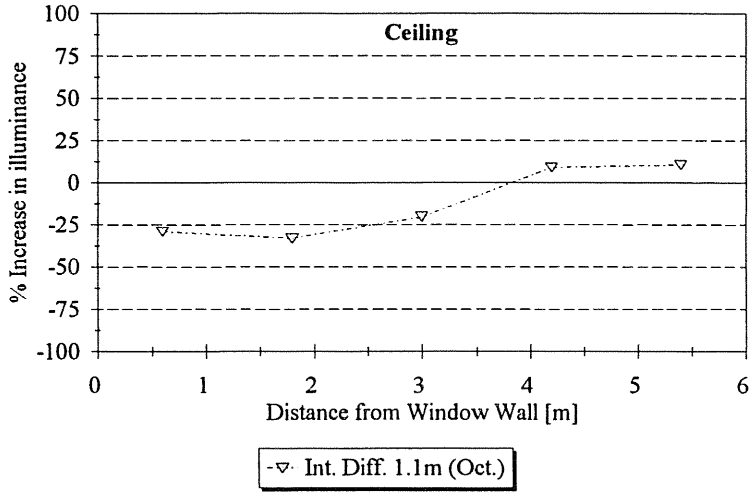


Figure 6.17 Direct Sun: The percentage change in illuminance level on the Ceiling for an interior diffuse light shelf relative to the reference room.

Table V.11 Average Illuminance level [lux] on the Ceiling for an interior diffuse light shelf adjusted to exterior vertical sky illuminance (70.000 lux).

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
LHD Pos. 1.1 m [lux] - Oct.	1930	1710	1390	910	460

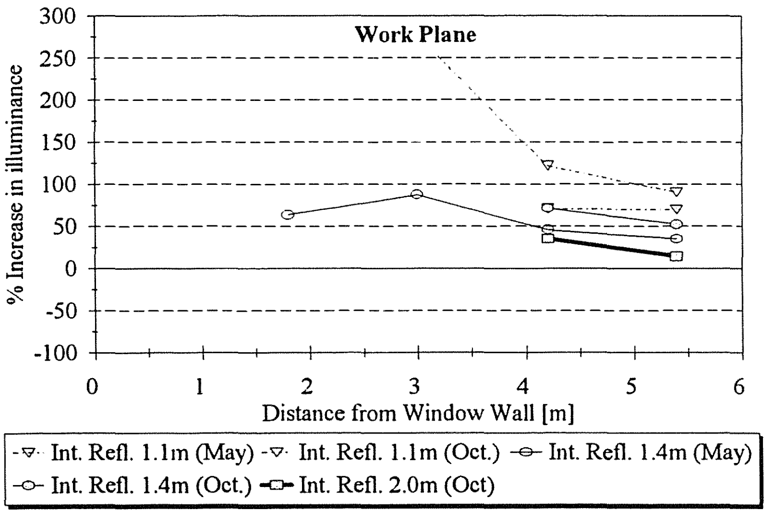


Figure 6.18 Direct Sun: The percentage change in illuminance level on the Work Plane for an interior reflective light shelf relative to the reference room.

Table V.12 Average Illuminance level [lux] on the Work Plane for an interior reflective light shelf adjusted to exterior vertical sky illuminance (70.000 lux).

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
LHR Pos. 1.1 m [lux] - May	3220	> 4000	> 4000	3770	1220	590
LHR Pos. 1.1 m [lux] - Oct.	1640	> 4000	> 4000	> 4000	1490	1010
LHR Pos. 1.4 m [lux] - May	4870	> 4000	3410	1860	800	420
LHR Pos. 1.4 m [lux] - Oct.	> 20000	2080	> 4000	> 4000	1390	870
LHR Pos. 2.0 m [lux] - Oct.	> 20000	> 4000	> 4000	990	1050	640

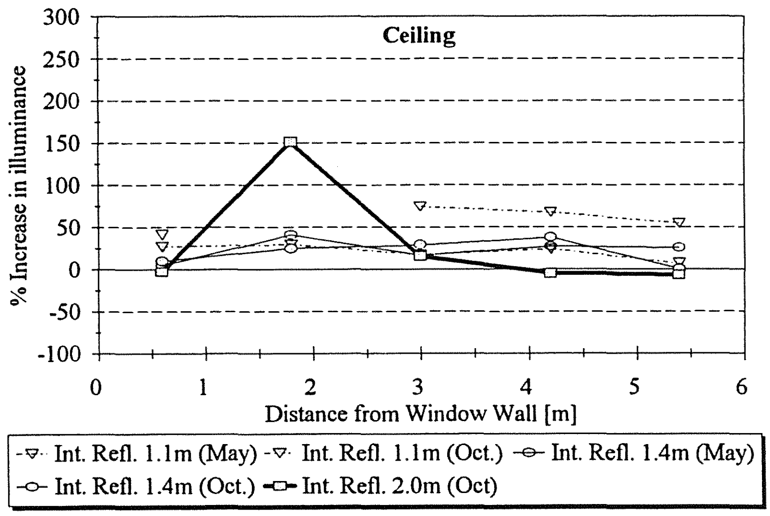


Figure 6.19 Direct Sun: The percentage change in illuminance level on the Ceiling for an interior reflective light shelf relative to the reference room.

Table V.13 Average Illuminance level [lux] on the Ceiling for an interior reflective light shelf adjusted to exterior vertical sky illuminance (70.000 lux).

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
LHR Pos. 1.1 m [lux] - May	3070	> 4000	1080	510	290
LHR Pos. 1.1 m [lux] - Oct.	1670	1650	1340	1070	630
LHR Pos. 1.4 m [lux] - May	2510	2180	730	390	220
LHR Pos. 1.4 m [lux] - Oct.	1170	1290	1270	1170	740
LHR Pos. 2.0 m [lux] - Oct.	900	2180	1010	830	980

Measurements on the ceiling, with the diffuse light shelf at the window-sill height, show that the illuminance level was increased at the back, even in the afternoon, by roughly 10% (Figure 6.17). With the reflective light shelf at 2 m (October), the illuminance level was boosted by 151% at 1.8 m, but reduced by 3% at 0.6 m (Figure 6.19). However, these findings were seldom reproducible since the reflected sunlight caused an extremely bright light band on the ceiling, with a luminance of approximately 30.000 cd/m^2. This discrepancy was allegedly caused by the reflected sunlight on the ceiling, which affected the area between two detectors. Similar tendencies will occur with the reflective light shelf at the lower positions, but the measurements were carried out by equal time separation from "noon" in the morning and the afternoon, which affects areas on the ceiling which were not measured. The illuminance level at the back was reduced by 5-7% with the reflective light shelf at 2 m, compared to the reference room.

Manual luminance measurements on the ceiling with the reflective light shelf were conducted in three different positions in both rooms (Table V.14). The luminance measurements show a ratio of roughly 1:1 between the luminance level at the window perimeter (0.6 m) and at the back (5.4 m). The illuminance level with the reflective light shelf at 2 m showed a similar ratio between the illuminance level at 0.6 m and at 5.4 m. The bright light band affected the area at 2-2.5 m from the window.

Table V.14 Luminance measurements on the ceiling in three different position (October) with the interior reflective light shelf and the reference room.

Interior Reflective Light shelf: Ceiling	Daylight Laboratory			Reference Room		
	0.6 m [cd/m^2]	3.0 m [cd/m^2]	5.4 m [cd/m^2]	0.6 m [cd/m^2]	3.0 m [cd/m^2]	5.4 m [cd/m^2]
LHR Pos. 1.1 m - Oct. (afternoon)	600	470	270	420	360	210
LHR Pos. 1.4 m - Oct. (afternoon)	440	490	310	350	320	240
LHR Pos. 2.0 m - Oct. (noon)	350	420	340	330	300	300

6.1.5 Exterior light shelf: Clear Sky with direct sun

The exterior light shelf shows similarly reduced shading efficiency for low solar altitudes (Table V.15 and Table V.17) to the interior light shelf. On clear days in September, the exterior light shelf at 2 m shaded direct sunlight at 1.2 m (3880 lux), while allowed direct penetration at 0.6 m and 1.8 m. Moving the light shelf to the lower position at 1.4 m caused the detector at 0.6 m to be shaded (5890 lux), while the detectors at 1.2-1.8 m were in direct sun.

In September, the *diffuse light shelf* at 2 m reduced the work plane illuminance level at 5.4 m by 10%, compared to the reference room, while the illuminance level was almost the same at 3-4.2 m (Figure 6.20). Moving the diffuse light shelf to 1.4 m increased the work plane illuminance level at 3-5.4 m by 8-20%, lowest at 5.4 m.

In September, the measurements with the *reflective light shelf* were carried out in the afternoon. This affected the relative work plane illuminance level compared to the reference room, due to the variation in distance to nearby adjacent sidewalls in the morning and afternoon (Figure 6.22). However, the reflective light shelf at 2 m showed only small reductions of the work plane illuminance level (1-4%) at 3-5.4 m, while the light shelf at 1.4 m increased the illuminance level at 3-5.4 m by 5-13%.

Measurements on the ceiling surface with the exterior diffuse light shelf at 2 m showed a reduced illuminance level at 3-5.4 m by 7-31%, highest at the back (Figure 6.21). Moving the light shelf to 1.4 m increased the illuminance level at 3-4.2 m by 22-31% and 11% at 5.4 m. Differences in the front half of the room are the result of the measurements with the light shelf at 1.4 m being carried out in the morning and afternoon. The afternooon measurements with the reflective light shelf at 2 m reduced the illuminance level at the back by 14-18%, while the lower position caused only small variations (2-5%) compared to the reference room (Figure 6.23).

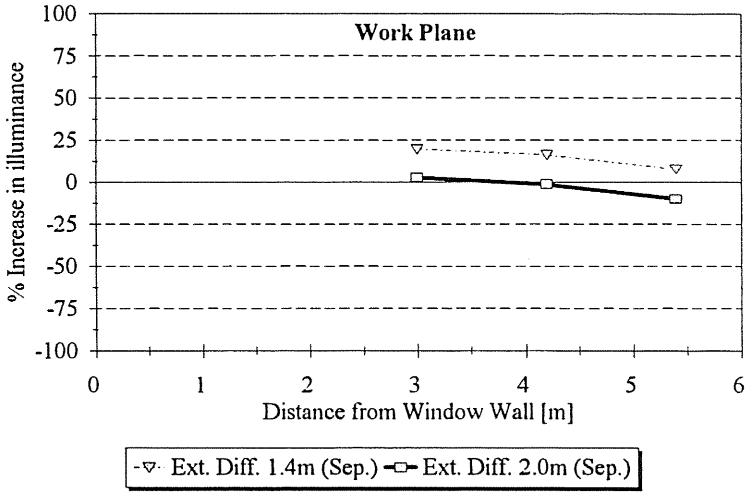


Figure 6.20 Direct Sun: The percentage change in illuminance level on the Work Plane for an exterior diffuse light shelf relative to the reference room.

Table V.15 Average Illuminance level [lux] on the Work Plane for an exterior diffuse light shelf adjusted to exterior vertical sky illuminance (70.000 lux).

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
LHD Pos. 1.4 [lux] - Sep.	5890	> 4000	> 4000	1750	960	550
LHD Pos. 2.0 [lux] - Sep.	> 20000	3880	> 4000	1360	780	450

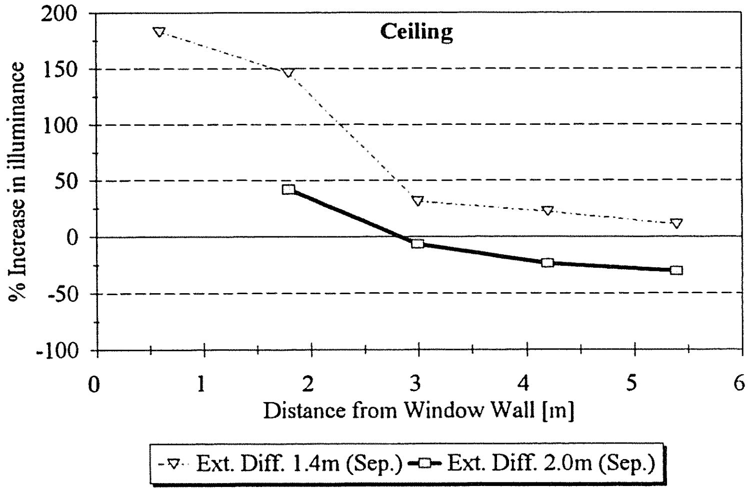


Figure 6.21 Direct Sun: The percentage change in illuminance level on the Ceiling for an exterior diffuse light shelf relative to the reference room.

Table V.16 Average Illuminance level [lux] on the Ceiling for an exterior diffuse light shelf adjusted to exterior vertical sky illuminance (70.000 lux).

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
LHD 1.4 m [lux] - Sep.	3810	2570	1050	650	360
LHD 2.0 m [lux] - Sep.	> 4000	1620	820	510	310

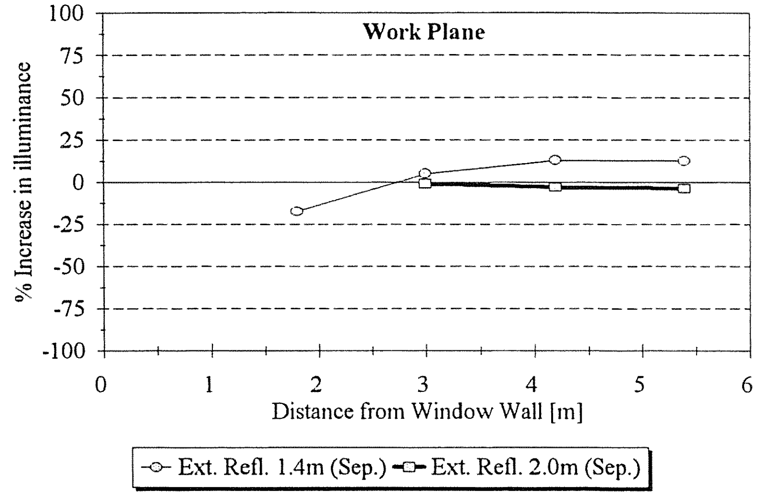


Figure 6.22Direct Sun: The percentage change in illuminance level on the Work Plane for an exterior reflective light shelf relative to the reference room.

Table V.17 Average Illuminance level [lux] on the Work Plane for an exterior reflective light shelf adjusted to exterior vertical sky illuminance (70.000 lux).

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
LHR Pos. 1.4 m [lux] - Sep.	3350	3200	2730	1750	1070	620
LHR Pos. 2.0 m [lux] - Sep.	> 20000	3920	3080	1560	900	540

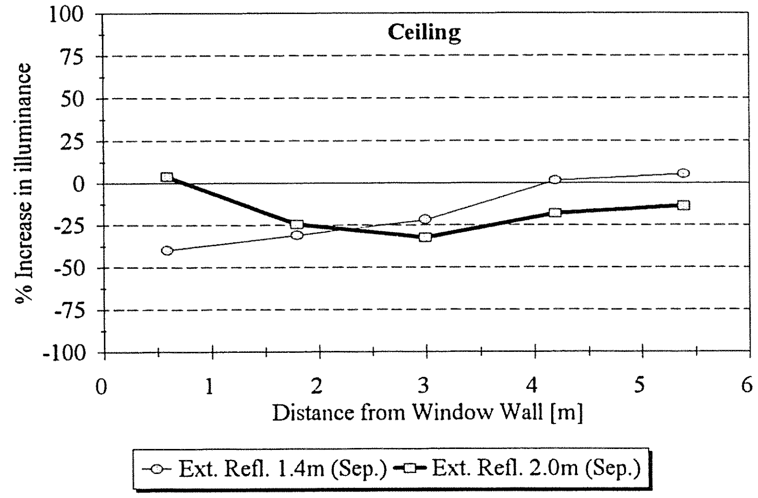


Figure 6.23 Direct Sun: The percentage change in illuminance level on the Ceiling for an exterior reflective light shelf relative to the reference room.

Table V.18 Average Illuminance level [lux] on the Ceiling for an exterior reflective light shelf adjusted to exterior vertical sky illuminance (70.000 lux).

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
LHR Pos. 1.4 m [lux] - Sep.	1960	1730	1220	800	450
LHR Pos. 2.0 m [lux] - Sep.	2720	1470	900	600	350

6.1.6 Subjective evaluation of the light shelf

The interior "quality" when using the interior and the exterior light shelf was assessed by illuminance measurements and by subjective evaluations. The subjective assessments, either from a sitting or standing position, were concentrated on glare problems and luminance distributions (window and ceiling), especially the variations in anterior and posterior parts of the room. The assessments of visual quality and distraction in the interior were supplemented with measurements of sky luminance and interior adaptation luminances for a line of sight towards the window.

Position 1 (2 m)

Assessments of the view-out when using the light shelf at 2 m, were affected by the location above the eye level, the geometry of the light shelf and the position of observation in the interior. Figure 6.24 shows that the system caused an annoying dividing line of the external view between the sky, the opposing building and the vegetation in the foreground. The interior light shelf caused an increased dissatisfaction compared with the exterior light shelf, since the exterior view and the overall interior perception were affected by the dominating, unfamiliar inward extending feature. The severity of dissatisfaction had a diminishing effect due to the simplicity of the self-made light shelf, but increasing the depth will increase the displeasure of the interior light shelf. Therefore, acceptable integration of an interior light shelf in the building design must emphasise the importance of the system as a coordinated and adopted part of the window design.

Figure 6.24 Interior photograph of the interior light shelf 2 m above the floor level, displaying the view-out function at a distance of 3 m from the window.

The subjective assessments of glare problems for the overcast and the clear sky conditions showed no general distinct differences between the reference room and the light shelf at 2 m. The light shelf partly shaded the front half of the room by reducing the patch of the visible sky (seated). Estimation of the discomfort glare experienced for an overcast sky (3.200 cd/m^2), with the DGI discomfort glare index, caused the glare rating of the reference room to be uncomfortable. The DGI index depends mainly on the luminance of the sky seen through the window, while the effect of interior adaptation luminance is less significant (see chapter 4). Chauvel conducted an evaluation of the DGR glare index and concluded that the *discomfort glare from a single window (except for a rather small one) is practically independent of size and distance from the observer but critically dependent on the sky luminance* [Chauvel 1982]. Even if the adjacent surfaces (sidewalls and ceiling) received more reflected light as a result of the light shelf, causing a slightly reduced contrast between the sky and the field of vision, it had no real effect on reducing discomfort glare. Interpretation of these subjective observations was merely the result of the simplified light shelf's geometry since it caused insignificant changes to the interior luminance level and had no real effect on reducing the exposure to the sky. The black coloured window frame increased the interior dissatifaction, since it caused a sharp, annoying contrast between the brightness of the sky and interior window facade (see Figure 6.24).

Figure 6.15 shows that the interior light shelf caused a slightly increased, non-uniform luminance distribution compared to the reference room, due to the shaded, intermediate area. The exterior light shelf produced a more uniform distribution by reducing the variation between the brightest and darkest part of the interior. For the overcast sky condition, both the interior and exterior light shelf caused, occasionally, the test room to be perceived brighter than the reference room, although the resulting work plane illuminance was reduced throughout the interior. These subjective assessments of the interior were indirectly emphasised by the difference in interior colours, from a predominately greenish interior in the reference room to a more white-dominated interior in the test room. This is generated by dominating, increased reflected skylight and the slightly reduced light from the exterior grass field.

Variations in the sun's elevation and the profile angle affected the areas where the reflected light from the light shelf struck the ceiling and walls in the room. For high solar altitudes (summer), no direct sunlight was reflected from the interior light shelf at 2 m to the room, because of the exterior overhang. In addition, the size and shape of the light shelf did not block the penetration of direct sunlight at low solar altitudes, causing the sunrays to penetrate both the window perimeter and the intermediate area of the room through the space between the light shelf and the ceiling surface, thus increasing the needs for additional shading. Reflected direct sunlight initiated a more distinct interior discomfort by the bright light band on the ceiling and the adjacent sidewalls. The diffuse reflection of the direct sun caused a moderate interior discomfort, while luminance measurements showed, for the reflective light shelf, that the bright light band had an intensity of approximately 30.000 cd/m^2 (an unscreened fluorescent lamp is equal to 10.000 cd/m^2).

Position 2 (1.4 m)

The unusual position of the light shelf 1.4 m above the floor level influenced the subjective evaluations of the performance for both the interior and exterior light shelf. An overall dissatisfaction of the exterior view was experienced, but this is merely affected by the light shelf being located below eye level when standing.

Problems with reflected glare arose, especially in a standing position, because direct sunlight and skylight were reflected off the surface directly into the field of view. Subjective dissatisfactions were primarily caused by the reflective light shelf, but also from the diffuse surface, submitting a similar effect as that experienced from direct glare. The magnitude of reflected glare was severe and intolerable, due to direct sunlight being reflected off the light shelf (reflective) causing tears in one's eyes and a radical reduction of visibility. Even if the position of observation was moved slightly away or deeper into the interior, it still generated a disabling effect on the interior since the brightness and intensity of the sky and sun, together with the reflective light shelf, were almost unchanged while the contrast between the bright and dark parts of the interior was increased. Looking directly at the reflective surface in an overcast sky condition resulted in the surface being perceived to be brighter than the sky luminance (6.000 cd/m^2). This is caused by the simultaneous contrast between the reflective surface and the overcast sky luminance since the light shelf, with an almost identical luminance level, appears brighter when seen against the darker background of the exterior view. The visual discomfort was reduced, when observed from a seated position, since the upper part of the light shelf was invisible. However, the subjective evaluation of glare problems was unchanged compared to the reference room, since the position of the light shelf caused no reduction or shade of the sky. The tendencies of changing the interior colours were similar to those observed for the light shelf position 2 m above the floor level.

Position 3 (1.1 m)

Moving the light shelf to the window-sill height caused the maximum possible increase of the interior illuminance level, causing similar or more severe subjective evaluations than those experienced in position 2.

6.2 *Performance of Venetian blinds*

Measurements of the Venetian blinds were conducted from September to the end of October 1994. The amount of daylight received in the interior depends on the sun's elevation and slat angle, since direct solar radiation and diffuse skylight are either obstructed, reflected and/or redirected. The intentions were to investigate the Venetian blinds' ability to increase daylight penetration while providing the interior with shade from direct sunlight and bright sky luminances, when needed. The results showed, for an overcast sky, that the Venetian blinds reduced the work plane illuminance level throughout the interior, compared to the reference room. On clear days with direct sun, only the downward tilted slat angle caused an efficient and acceptable shading of direct sun. Glare and visual distractions were affected by the slat angle, the slat surface and the distance between the slats. The measured situations of the Venetian blinds were: reflective with small and large scaled slats, white coloured with medium scaled slats, white/reflective (medium) and black coloured (medium). The slat width varied between: small 16, medium 25 and large 35 mm. The white/reflective blinds were white coloured at the top with a reflective under side. The blinds were evenly spaced with a distance between the slats equal to 80% of the slat width (width/distance equal to 1.2), to maintain a slight overlap when fully closed.

Figure 6.25 shows the different slat angles measured, where light is received and transmitted differently to the interior from the sky, sun and the exterior ground surface. Upward tilted slat angles, described by negative angles (e.g. VB -30°), transmit light primarily from the sky and sun. Downward tilted slat angles, described by positive angles, transmit light primarily from the exterior ground surface. The main difference between the two strategies is due to the reduced intensity received (overcast) from the ground, which is approximately 10% of the intensity received from the sky.

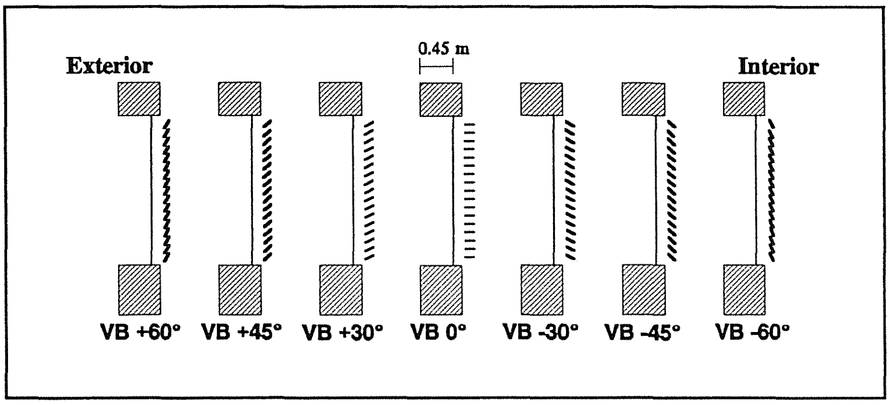


Figure 6.25 A principle drawing displaying the different slat angles of the investigated Venetian blinds (VB).

6.2.1 Venetian blinds 0°: Overcast Sky

Measurements with the Venetian blinds in a horizontal slat angle position (VB 0°), caused a reduced interior illuminance level on the work plane throughout the interior (Figure 6.27). Blinds with a horizontal slat angle receive light almost equally from the sky and the exterior ground. The light is transmitted directly through the blinds for a profile angle of 0-40°. Outside this range, the incident light is subjected to increased reflection, varying from a single reflection to a great number of inter-reflections depending on the reflectance properties and the distance between the slats.

The large scaled, reflective Venetian blinds (35 mm) caused the smallest reductions of the interior work plane illuminance level. The measurements showed that the work plane illuminance level was reduced by 14-74% compared to the reference room. The highest reductions were measured at the window perimeter (60-74%) and the lowest reduction (14%) at the back (4.2-5.4 m) (Figure 6.27). The reduced work plane illuminance shows an unfavourable shading "efficiency" for the overcast sky, emphasising the necessity of the system's movability. Table V.20 shows the average daylight factors on the work plane for the Venetian blinds with a horizontal slat angle 0°. For example, an overcast sky with the exterior horizontal illuminance level equal to 10000 lux, causes a work plane illuminance at 0.6 m to be reduced from 1390 lux (reference room) to 380 lux (Venetian blinds).

Reducing the size to the small, reflective slats, caused an additional reduction (7%) of the work plane illuminance at 1.8-5.4 m, compared with the large scaled, reflective Venetian blinds. The illuminance level was reduced by 21-29% in the intermediate area and 21% at the back compared to the reference room (Figure 6.27). The white coloured and the white/reflective Venetian blinds caused similar reductions to those with the small scaled, reflective Venetian blinds. The small variations throughout the interior are practically negligible, but the main difference between the three blind systems occurs 0.6 m from the window. The white/reflective Venetian blinds increased the inter-reflection between the slats, reducing the illuminance level from 74% to about 67% at the window perimeter (0.6 m). However, this tendency was reversed (3%) at the back, so that the reduction was now 25% at 4.2-5.4 m. The black, diffuse Venetian blinds are only considered to illustrate the worst-case of light transmission to the interior. Interior measurements for a black coloured Venetian blind showed that the work plane illuminance level was reduced by 30-88%, but the general variation in the interior was similar to the other blind systems.

Measurements on the ceiling are shown in Figure 6.28. The large scaled, reflective Venetian blind boosted the illuminance level by 54% at 1.8 m from the window, but the increase was only 4% at 0.6 m. The difference at the window perimeter between the small and the large scaled, reflective Venetian blinds was allegedly caused by a different curvature of the slats. The difference is emphasised by a reduced illuminance level for the small reflective Venetian blind in the intermediate area and at the back. The white and the white/reflective blind systems caused a more diffusively formed light distribution of incident light, increasing the illuminance level at the window perimeter by 10-25%. The difference between the two systems is that the white/reflective under side provides a higher fraction of the exterior ground reflected light to be diffusively distributed to the interior. The black Venetian blinds reduced the overall interior illuminance level throughout the ceiling surface (36-75%).

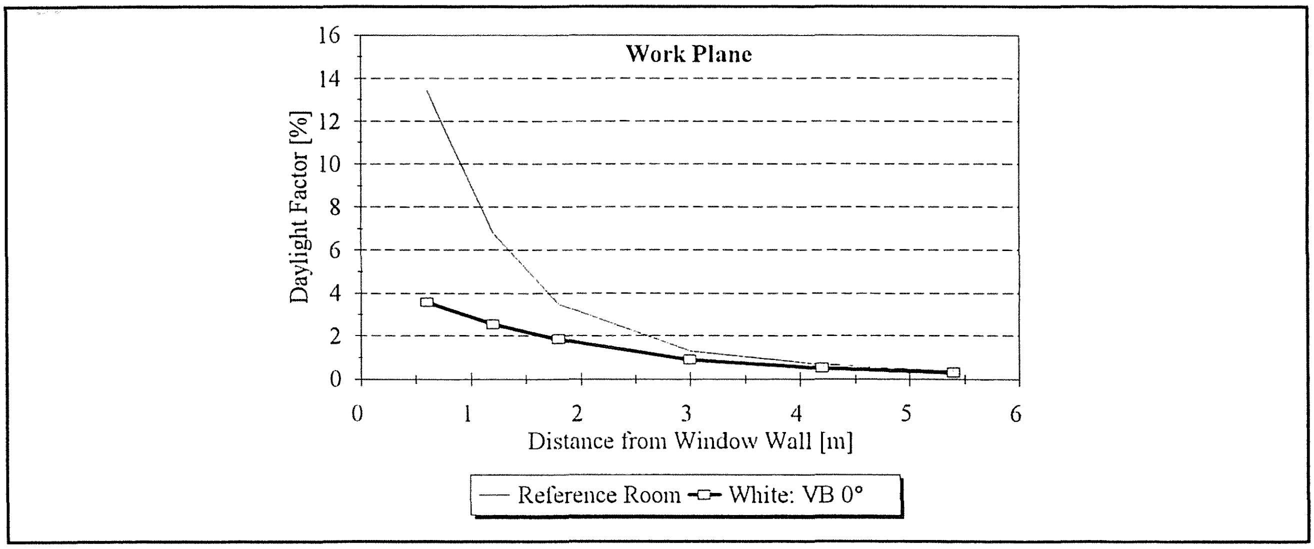


Figure 6.26 Overcast Sky: The daylight factor [%] on the Work Plane for a white reflective Venetian blind [VB 0°] compared to the reference room.

Table V.19 Average Daylight Factor [%] on the work plane for a white coloured Venetian blind with horizontal slat angles (VB 0°) compared to the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	13.5	6.8	3.5	1.3	0.7	0.4
VB White 0°	3.6	2.6	1.9	0.9	0.5	0.3

Figure 6.26 and Table V.19 show the daylight factors on the work plane for the white reflective Venetian blinds with a horizontal slat angle. Figure 6.26 shows that the overall work plane illuminance distribution resulted in a more moderate, uniform variation between the brightest and darkest part of the interior. The measurements on the work plane show that the usually recommended daylight factor of 2% occurs at a distance roughly 1.7 m from the window wall.

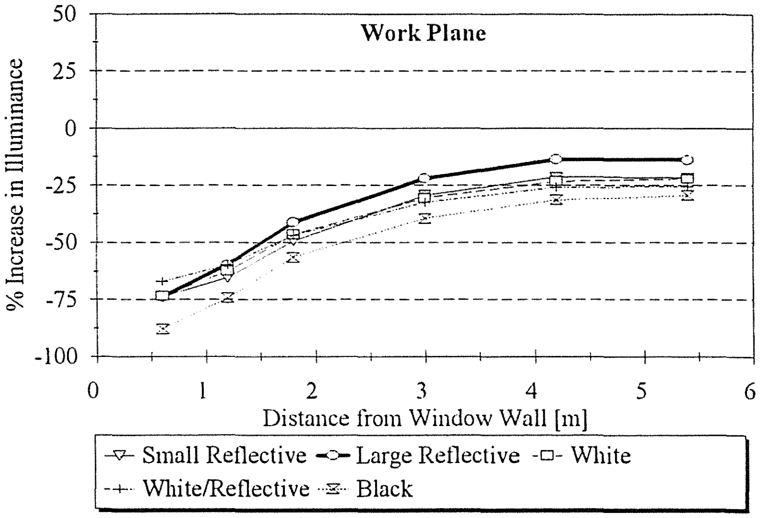


Figure 6.27 Overcast Sky: The percentage change in illuminance level on the Work Plane for Venetian blinds with a slat angle of 0° relative to the reference room.

Table V.20 Average Daylight Factors [%] on the Work Plane for all the VB 0° and the reference room.

Work Plane	**0.6 m**	**1.2 m**	**1.8 m**	**3.0 m**	**4.2 m**	**5.4 m**
Reference Room	13.9±0.4	7.4±0.4	3.9±0.2	1.5±0.2	0.8±0.1	0.4
VB Reflective Small	3.6	2.6	2.0	1.1	0.6	0.3
VB Reflective Large	3.8	3.2	2.5	1.3	0.8	0.4
VB White	3.6	2.6	1.9	0.9	0.5	0.3
VB White/Reflective	4.4	2.9	2.0	1.0	0.6	0.3
VB Black	1.7	1.9	1.7	0.9	0.5	0.3

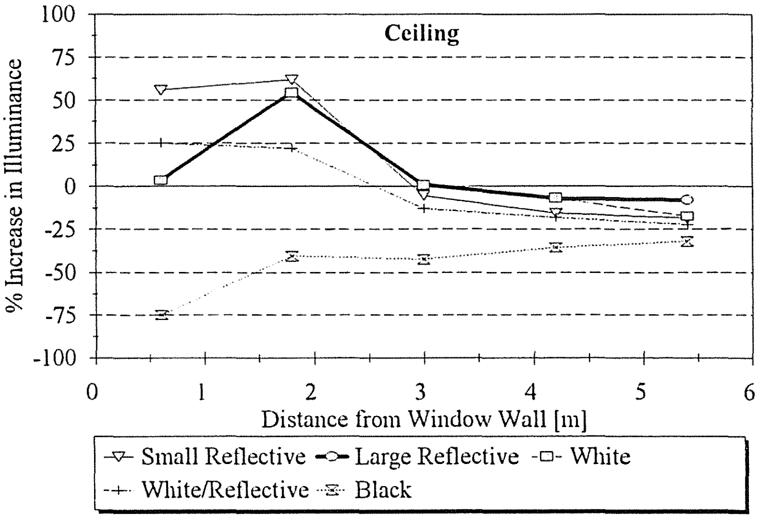


Figure 6.28 Overcast Sky: The percentage change in illuminance level on the Ceiling for Venetian blinds with a slat angle of 0° relative to the reference room.

Table V.21 Average Daylight Factors [%] on the Ceiling for all the VB 0° and the reference room.

Ceiling	**0.6 m**	**1.8 m**	**3.0 m**	**4.2 m**	**5.4 m**
Reference Room	1.5±0.1	1.0±0.1	0.6	0.4	0.2
VB Reflective Small	2.4	1.7	0.6	0.3	0.2
VB Reflective Large	1.6	1.7	0.7	0.4	0.2
VB White	1.5	1.2	0.5	0.3	0.2
VB White/Reflective	1.8	1.2	0.5	0.3	0.2
VB Black	0.4	0.6	0.4	0.2	0.2

6.2.2 Venetian blinds ±30°: Overcast Sky

The upward tilted slat angle of VB −30° transmits the incident light from the sky directly through at a profile angle of 0-57°. The profile angle for directly transmitted ground-reflected light is reduced from 40° to 21°. Rotating the blinds to a downward tilted slat angle of VB +30° causes an inverted range of the profile angle equal to VB −30° of the exterior ground reflected light.

Upward tilted blinds reduced the work plane illuminance level at the window perimeter by 35-45% (0.6-1.8 m) for all blinds, compared to the reference room (Figure 6.31). The variations of the work plane illuminance level in the intermediate area and at the back show the difference between the diffuse and the reflective slat surfaces. The large scaled, reflective Venetian blinds reduced the work plane illuminance level at 3-5.4 m by 25%. The differences between the two reflective blinds systems, mainly caused by different curvature of the slats, show that the small scaled Venetian blinds only reduced the work plane illuminace level by 10% at 3-5.4 m. The diffuse, white coloured blinds showed the best performance relative to the large scaled, reflective blinds. The work plane illuminance level was reduced in the intermediate area and at the back by roughly 15%.

Downward tilted blinds showed a similar reduction of the work plane illuminance level for all blind systems, except the black Venetian blinds, varying from approximately 57-87% (Figure 6.33). The lowest reduction was caused by the large scaled, reflective Venetian blinds, where the light level was reduced by 75-82% at the window perimeter and 57% at the back (4.2-5.4 m).

Measurements on the ceiling, with upward tilted slat angle, show that for the large scaled reflective Venetian blinds, the illuminance level was reduced by 10-49%, highest at the window perimeter (Figure 6.32). The diffuse Venetian blinds reduced the discrepancies at the window perimeter (33-34%), while the difference was reduced at the back (10-25%), compared to the reference room. Downward tilted reflective blinds boosted the illuminance level at 0.6 m by 76-89%, while the increase was more moderate but still significant for the diffuse blinds (37-40%) (Figure 6.34). The illuminance level was reduced equally from 3-5.4 m by roughly 50% compared to the reference room, because of the reduced penetration of the exterior, ground- reflected light.

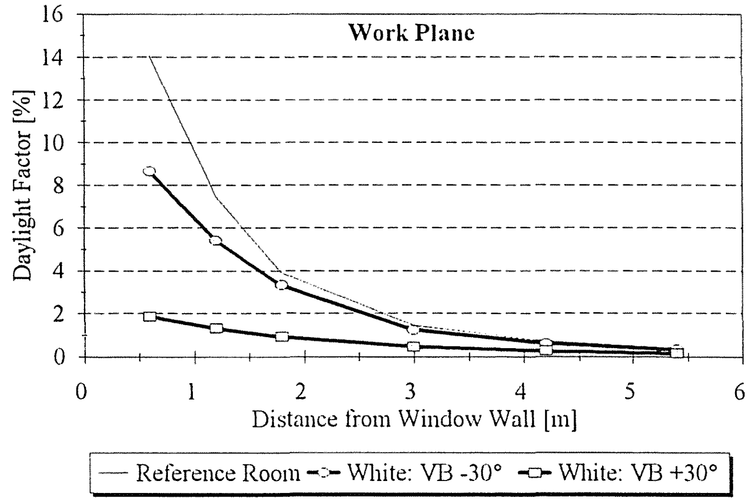


Figure 6.29 Overcast Sky: The daylight factor [%] on the Work Plane for white coloured Venetian blinds [VB ±30°] compared to the reference room.

Table V.22 Average Daylight Factor [%] on the work plane for white coloured Venetian blinds with ±30° tilted slat angle compared to the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	14.0	7.5	3.9	1.5	0.7	0.4
VB White -30°	8.7	5.4	3.3	1.2	0.6	0.3
VB White +30°	1.9	1.3	0.9	0.5	0.3	0.2

Table V.22 shows the daylight factors (DF) on the work plane for the white coloured Venetian blinds with the upward and downward tilted slat angles (VB ± 30°). The upward tilted slat angle (− 30°) increased the variation between the brightest and darkest part of the interior (Figure 6.29). The measurements on the work plane show that the usually recommended daylight factor of 2% occurs at a distance of approximately 2.5 m from the window. The downward tilted slat angle (+ 30°) to a more traditional position caused partial shading of the direct sky component, providing an overall interior illuminance level below a daylight factor of 2%.

6.2.3 Venetian blinds ±45°: Overcast Sky

The upward tilted slat angle of VB −45° transmits the incident light from the sky directly through at a profile angle of 0-65°. The profile angle for transmitting the ground-reflected light is reduced from 40° to 10°. Rotating the blinds to a downward tilted slat angle of VB +45° caused an inverted range of the profile angle equal to VB −45°.

Upward tilted blinds show similarly reduced, relative work plane illuminance level for all blinds (except the black) throughout the interior, by 21-51%, with the highest reductions of 41-51% at 3.0-5.4 m (Figure 6.35). Downward tilted blinds caused the work plane illuminance level to be reduced by approximately 69-93%, highest at the window perimeter (Figure 6.37).

Measurements on the ceiling surface with upward tilted slat angle, show that the illuminance level was reduced by 28-60%, highest at the window perimeter for the large scaled, reflective Venetian blinds (Figure 6.36). The difference between the reflective and the diffuse Venetian blinds is practically negligible for downward tilted blinds (Figure 6.38). Downward tilted blinds increase the illuminance level at 0.6 m by 25-38%, while the illuminance level was reduced equally from 3-5.4 m by 46-64% compared to the reference room (Figure 6.34).

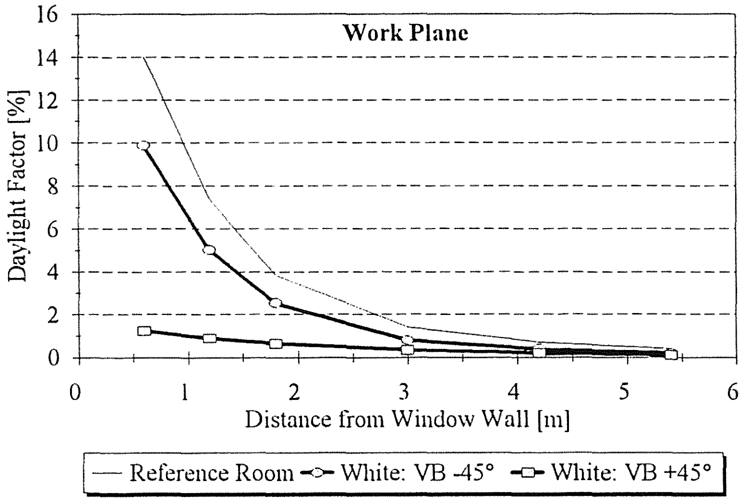


Figure 6.30 Overcast Sky: The daylight factor [%] on the Work Plane for white coloured Venetian blinds [VB ±45°] compared to the reference room.

Table V.23 Average Daylight Factor [%] on the work plane for white coloured Venetian blinds with ±45° tilted slat angle compared to the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	14.0	7.4	3.8	1.4	0.7	0.4
VB White -45°	9.9	5.0	2.5	0.8	0.4	0.2
VB White +45°	1.3	0.9	0.6	0.3	0.2	0.1

Table V.23 shows the daylight factors (DF) on the work plane for the white coloured Venetian blinds with upward and downward tilted slat angles. The upward tilted angle (−45°) increased the daylight factors in the window perimeter causing a DF of 2% at a distance of approximately 2.2 m from the window (Figure 6.30). Inverting the slat angles (+45°) to a typical, closed position caused the interior illuminance level to be reduced below a DF of 1% throughout the interior, except at 0.6 m.

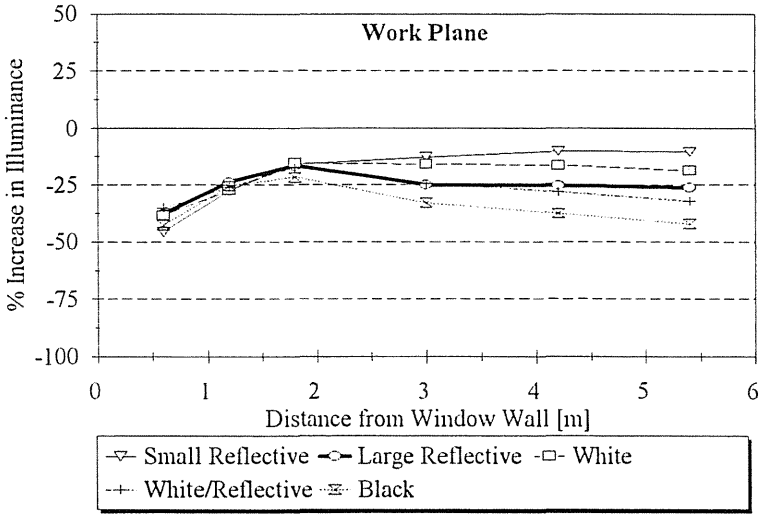


Figure 6.31 Overcast Sky: The percentage change in illuminance level on the Work Plane for Venetian blinds with a slat angle of -30° relative to the reference room.

Table V.24 Average Daylight Factors [%] on the Work Plane for all the VB -30° and the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	14.5±0.4	7.5±0.4	3.9±0.3	1.5±0.2	0.8±0.1	0.4
VB Reflective Small	7.5	5.1	3.0	1.2	0.6	0.4
VB Reflective Large	9.4	5.9	3.4	1.1	0.6	0.3
VB White	8.7	5.4	3.3	1.2	0.6	0.3
VB White/Reflective	8.4	5.1	3.0	1.0	0.5	0.3
VB Black	8.2	5.9	3.4	1.2	0.5	0.3

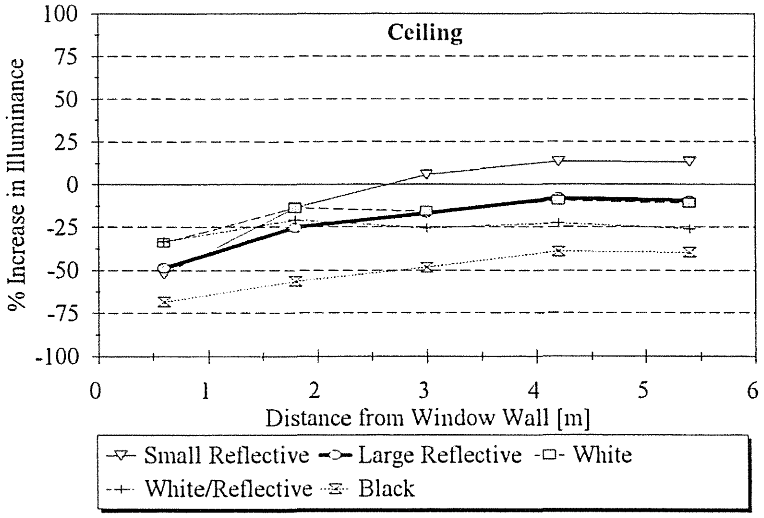


Figure 6.32 Overcast Sky: The percentage change in illuminance level on the Ceiling for Venetian blinds with a slat angle of -30° relative to the reference room.

Table V.25 Average Daylight Factors [%] on the Ceiling for all the VB -30° and the reference room.

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	1.5±0.1	1.0	0.6	0.4	0.2
VB Reflective Small	0.8	0.9	0.6	0.4	0.2
VB Reflective Large	0.8	0.8	0.5	0.3	0.2
VB White	1.0	0.9	0.5	0.3	0.2
VB White/Reflective	1.0	0.8	0.4	0.3	0.2
VB Black	0.5	0.5	0.4	0.2	0.2

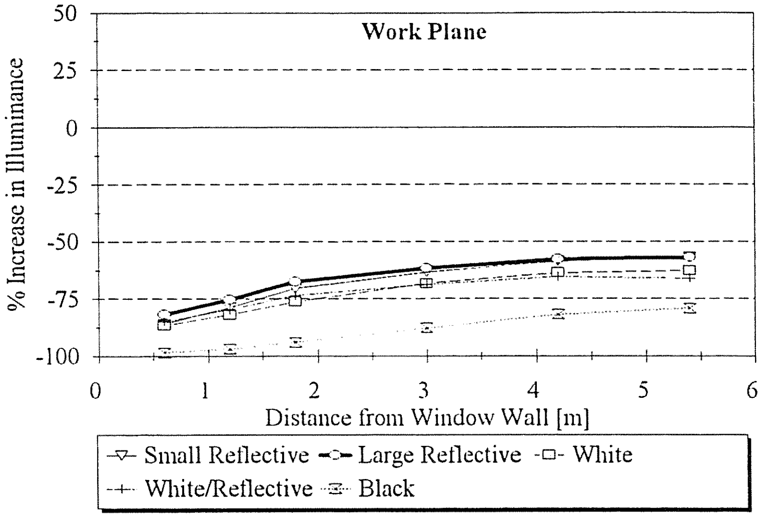


Figure 6.33 Overcast Sky: The percentage change in illuminance level on the Work Plane for Venetian blinds with a slat angle of +30° relative to the reference room.

Table V.26 Average Daylight Factors [%] on the Work Plane for all the VB +30° and the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	14.2±0.4	7.7±0.2	4.2±0.2	1.7±0.1	0.7	0.4
VB Reflective Small	2.1	1.7	1.2	0.6	0.3	0.2
VB Reflective Large	2.7	2.0	1.4	0.7	0.4	0.2
VB White	1.9	1.3	0.9	0.5	0.3	0.2
VB White/Reflective	2.2	1.6	1.1	0.5	0.3	0.2
VB Black	0.2	0.3	0.3	0.2	0.1	0.1

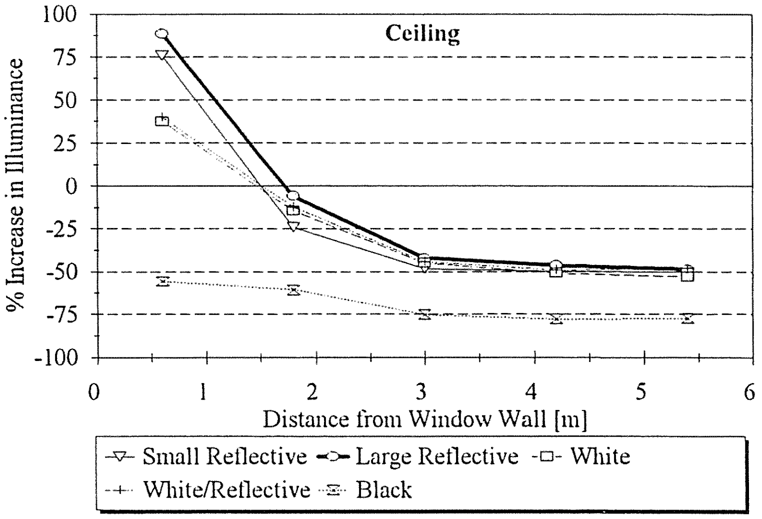


Figure 6.34 Overcast Sky: The percentage change in illuminance level on the Ceiling for Venetian blinds with a slat angle of +30° relative to the reference room.

Table V.27 Average Daylight Factors [%] on the Ceiling for all the VB +30° and the reference room.

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	1.6	1.1	0.7	0.4	0.2
VB Refl. Small	2.7	0.8	0.3	0.2	0.1
VB Refl. Large	3.0	1.0	0.4	0.2	0.1
VB White	2.1	0.9	0.3	0.2	0.1
VB White/Refl.	2.2	0.9	0.4	0.2	0.1
VB Black	0.7	0.4	0.2	0.1	0.1

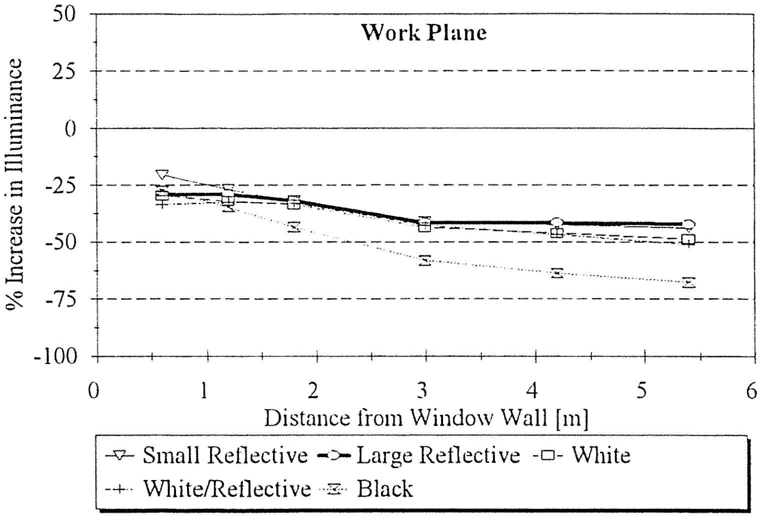


Figure 6.35 Overcast Sky: The percentage change in illuminance level on the Work Plane for Venetian blinds with a slat angle of -45° relative to the reference room.

Table V.28 Average Daylight Factors [%] on the Work Plane for all the VB -45° and the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	14.0±0.1	7.7±0.2	4.4±0.4	1.6±0.2	0.7±0.2	0.4±0.1
VB Reflective Small	11.0	5.8	3.0	1.0	0.5	0.3
VB Reflective Large	10.0	5.2	2.5	0.7	0.4	0.2
VB White	9.9	5.0	2.5	0.8	0.4	0.2
VB White/Reflective	9.3	5.0	2.6	0.8	0.4	0.2
VB Black	11.0	5.5	2.6	0.7	0.4	0.2

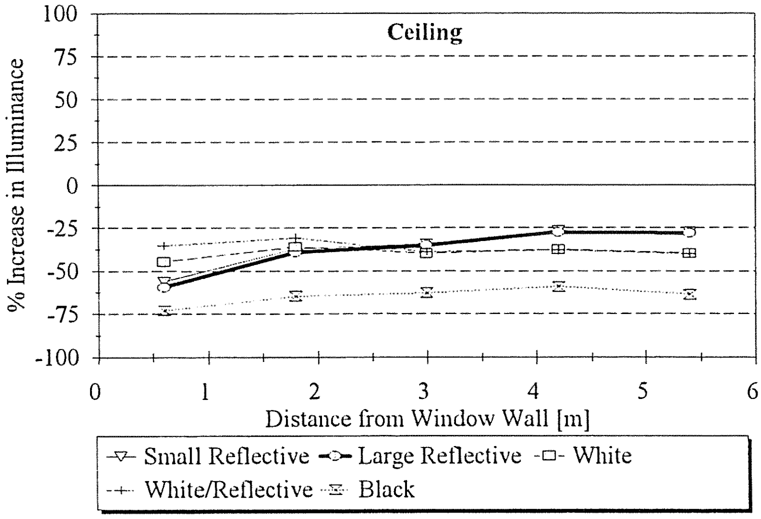


Figure 6.36 Overcast Sky: The percentage change in illuminance level on the Ceiling for Venetian blinds with a slat angle of -45° relative to the reference room.

Table V.29 Average Daylight Factors [%] on the Ceiling for all the VB -45° and the reference room.

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	1.5	1.0±0.1	0.6	0.4	0.2
VB Reflective Small	0.7	0.7	0.4	0.3	0.2
VB Reflective Large	0.6	0.6	0.4	0.2	0.1
VB White	0.8	0.6	0.4	0.2	0.1
VB White/Reflective	1.0	0.7	0.4	0.2	0.1
VB Black	0.4	0.4	0.3	0.2	0.1

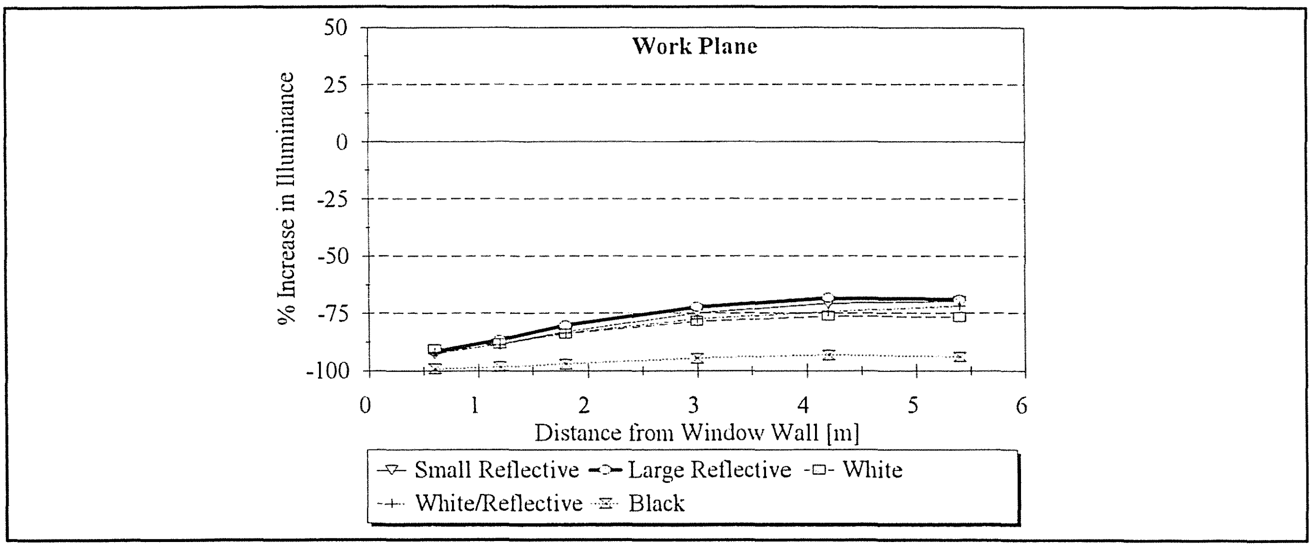


Figure 6.37 Overcast Sky: The percentage change in illuminance level on the Work Plane for Venetian blinds with a slat angle of +45° relative to the reference room.

Table V.30 Average Daylight Factors [%] on the Work Plane for all the VB +45° and the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Roome	14.1±0.4	7.6±0.1	4.1	1.6	0.8	0.5
VB Reflective Small	1.0	0.9	0.7	0.4	0.2	0.1
VB Reflective Large	1.2	1.0	0.8	0.4	0.3	0.2
VB White	1.3	0.9	0.6	0.3	0.2	0.1
VB White/Reflective	1.1	0.9	0.7	0.4	0.2	0.1
VB Black	0.1	0.1	0.1	0.1	≈ 0.0	≈ 0.0

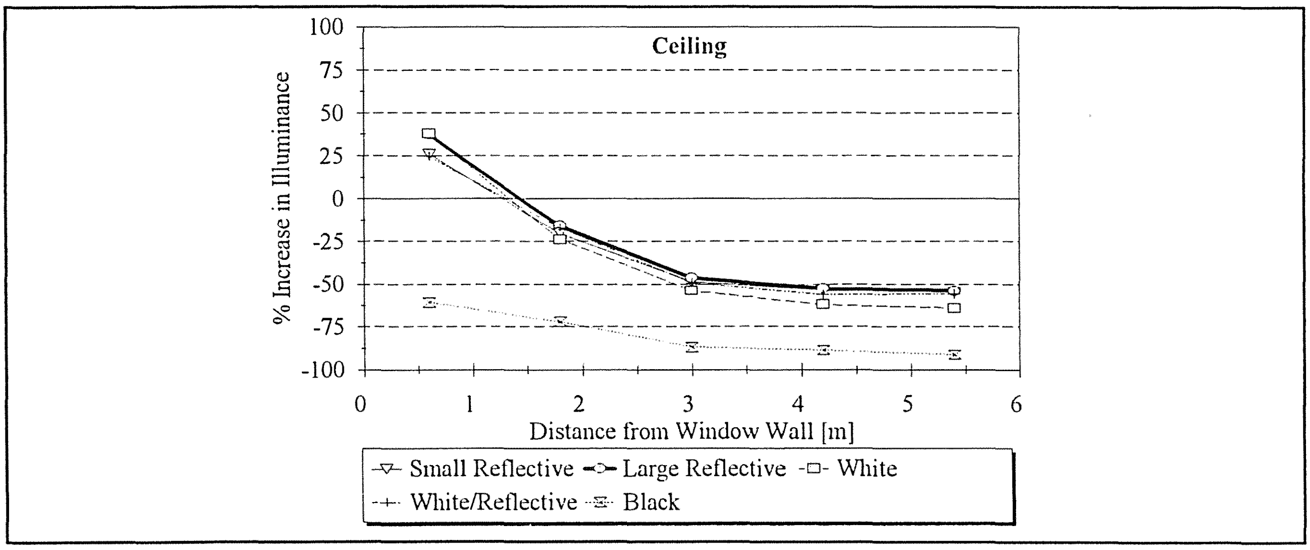


Figure 6.38 Overcast Sky: The percentage change in illuminance level on the Ceiling for Venetian blinds with a slat angle of +45° relative to the reference room.

Table V.31 Average Daylight Factors [%] on the Ceiling for all the VB +45° and the reference room.

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	1.5±0.1	1.0	0.6	0.4	0.2
VB Reflective Small	2.0	0.8	0.3	0.2	0.1
VB Reflective Large	2.1	0.9	0.4	0.2	0.1
VB White	1.9	0.8	0.3	0.1	0.1
VB White/Reflective	1.9	0.9	0.3	0.2	0.1
VB Black	0.6	0.3	0.1	≈ 0.0	≈ 0.0

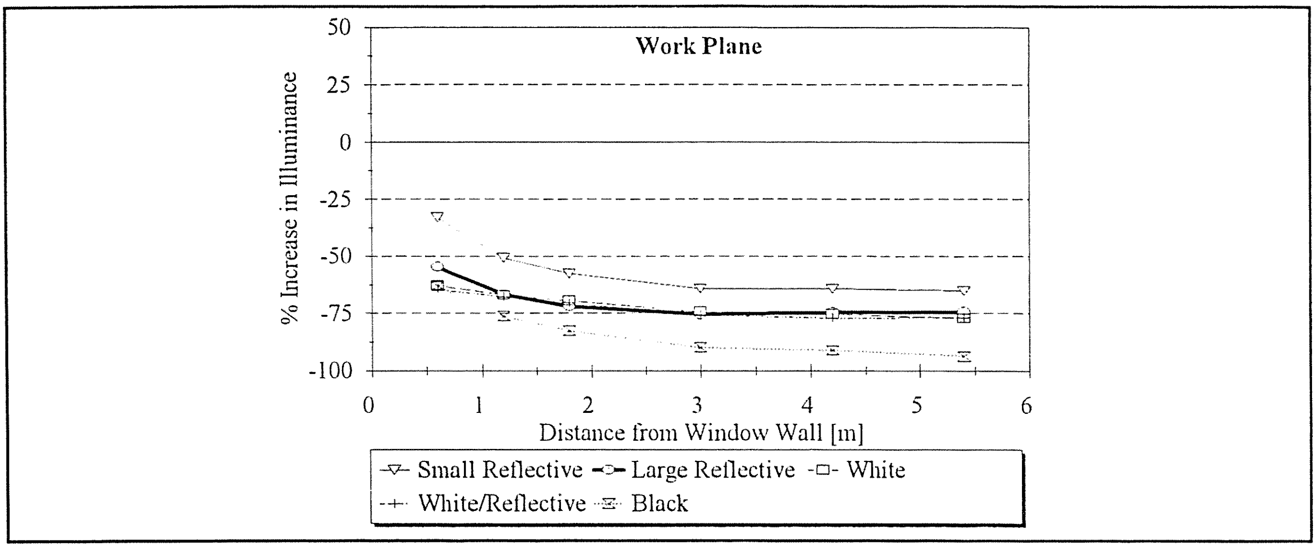


Figure 6.39 Overcast Sky: The percentage change in illuminance level on the Work Plane for Venetian blinds with a slat angle of -60° relative to the reference room.

Table V.32 Average Daylight Factors [%] on the Work Plane for all the VB -60° and the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	14.5±0.5	7.7±0.4	4.1±0.4	1.6±0.2	0.8±0.1	0.5
VB Reflective Small	9.4	3.8	1.8	0.6	0.3	0.2
VB Reflective Large	7.0	2.9	1.3	0.4	0.2	0.1
VB White	5.0	2.3	1.1	0.4	0.2	0.1
VB White/Reflective	5.4	2.7	1.3	0.4	0.2	0.1
VB Black*	6.9	2.6	1.1	0.3	0.1	0.1

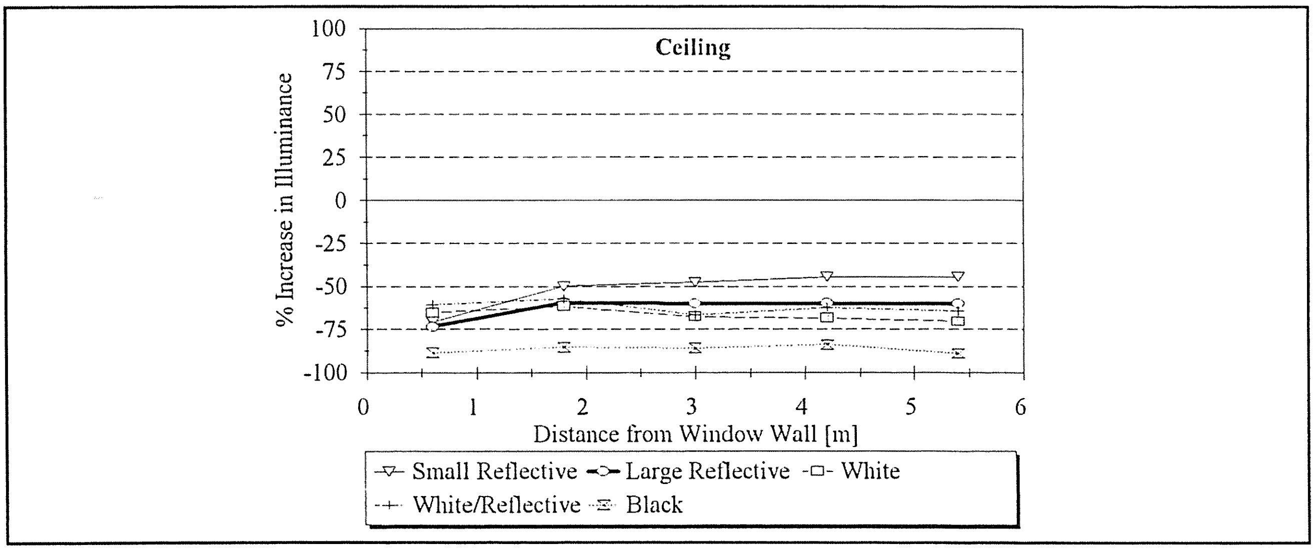


Figure 6.40 Overcast Sky: The percentage change in illuminance level on the Ceiling for Venetian blinds with a slat angle of -60° relative to the reference room.

Table V.33 Average Daylight Factors [%] on the Ceiling for all the VB -60° and the reference room.

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	1.6	1.1	0.7	0.4	0.2
VB Reflective Small	0.5	0.5	0.3	0.2	0.1
VB Reflective Large	0.4	0.4	0.3	0.2	0.1
VB White	0.5	0.4	0.2	0.1	0.1
VB White/Reflective	0.6	0.5	0.2	0.2	0.1
VB Black*	0.2	0.2	0.1	0.1	≈ 0.0

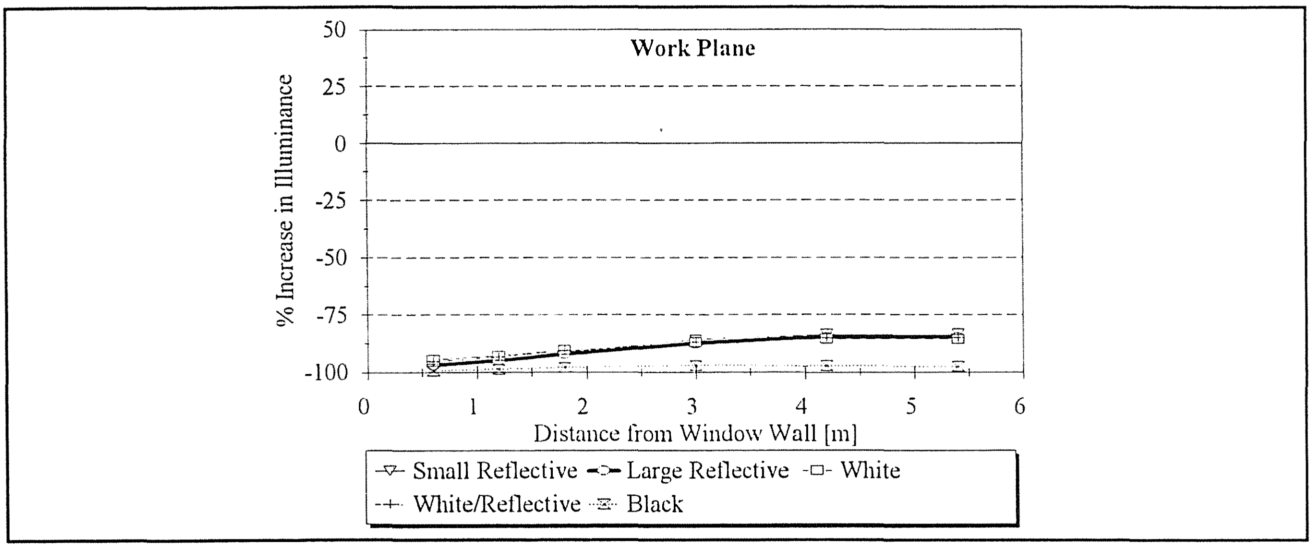


Figure 6.41 Overcast Sky: The percentage change in illuminance level on the Work Plane for Venetian blinds with a slat angle of +60° relative to the reference room.

Table V.34 Average Daylight Factors [%] on the Work Plane for all the VB +60° and the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	14.1±0.4	7.7±0.2	4.2±0.2	1.7±0.1	0.8	0.5
VB Reflective Small	0.4	0.4	0.4	0.2	0.1	0.1
VB Reflective Large	0.4	0.4	0.3	0.2	0.1	0.1
VB White	0.8	0.6	0.4	0.2	0.1	0.1
VB White/Reflective	0.7	0.5	0.4	0.2	0.1	0.1
VB Black	0.1	0.1	0.1	0.1	≈ 0.0	≈ 0.0

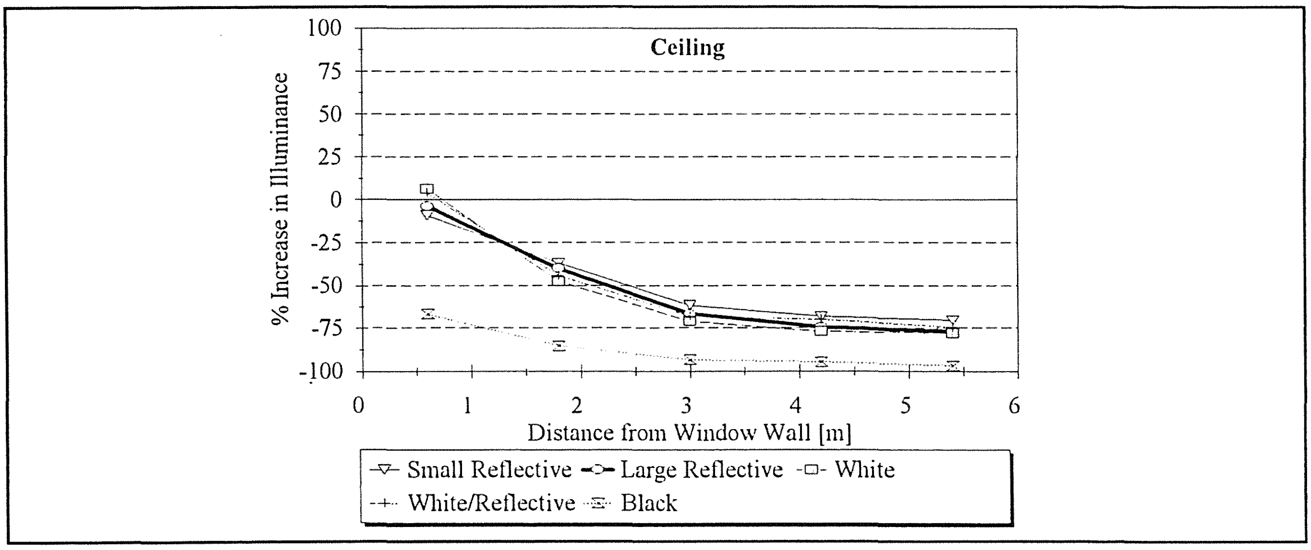


Figure 6.42 Overcast Sky: The percentage change in illuminance level on the Ceiling for Venetian blinds with a slat angle of +60° relative to the reference room.

Table V.35 Average Daylight Factors [%] on the Ceiling for all the VB +60° and the reference room.

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	1.6	1.1	0.7	0.4	0.2
VB Reflective Small	1.4	0.6	0.2	0.1	≈ 0.0
VB Reflective Large	1.5	0.6	0.2	0.1	≈ 0.0
VB White	1.6	0.5	0.2	0.1	≈ 0.0
VB White/Reflective	1.7	0.6	0.2	0.1	≈ 0.0
VB Black	0.5	0.2	≈ 0.0	≈ 0.0	≈ 0.0

6.2.4 Venetian blinds ±60°: Overcast Sky

The upward tilted slat angle of VB −60° transmits the incident light from the sky directly through at a profile angle of 0-74°, while directly transmitted, ground-reflected light is excluded. Downward tilted slat angle causes an inverted acceptance range equal to VB −60°.

Upward and downward tilted blinds reduced the work plane illuminance level throughout the interior by 54-77% and 85-97%, respectively (Figure 6.39 and Figure 6.41). Measurements on the ceiling surface show that the upward tilted slats reduced the illuminance level by 61-82% (Figure 6.40). Downward tilted blinds showed almost the same illuminance level as the reference room at 0.6 m, while the illuminance level was reduced equally from 3-5.4 m by 66-78% (Figure 6.42).

6.2.5 Large Reflective Venetian blinds: Clear Sky with direct sun

Measurements of the Venetian blinds for a clear sky with direct sun in October 1994, were conducted by equal time separation from noon, in the morning and afternoon, respectively. Only three different blind systems are presented, but the resulting interior illuminance level includes both the maximum and minimum possible quantity of daylight received. The interior work plane illuminance (in lux) has been adjusted relative to a fixed reference value of the exterior vertical sky illuminance on the facade (70.000 lux).

Table V.37 and Table V.38 show the adjusted interior illuminance level in lux on the work plane and ceiling, respectively. Horizontal and upward tilted slats (0 to 45°), caused the detectors in the window perimeter zone (0.6 m > 20.000 lux) and in the intermediate area (1.2-3.0 m > 4.000 lux) to be in a state of saturation. These slat angles are unsuited for shading of the front half (0.6-3 m), since they result in reduced control of the transmitted direct sunlight through the blinds system. Only the downward tilted slat angles caused an efficient and acceptable shading of the direct sun.

Only horizontal blinds (VB 0°) increased the work plane illuminance level at the back by 6-16% (4.2-5.4 m), compared to the reference room (Figure 6.43). Tilted slat angles caused the incident light either to be redirected back to the exterior and/or caused an increased inter-reflection between the slats. Upward tilted slat angles of -30° and -45° reduced the work plane illuminance level at the back by 26-29% and 36-40%, respectively. Closing the blinds, either upward or downward, showed the highest reduction at the back (56-67%). The main difference between the two closed positions is due to the reduced intensity received from the exterior ground which is approximately 10% of the intensity received from the sky. Downward tilted slat angles of +30° and +45° showed similar reduction as the equal upward tilted angles at the back (Figure 6.43).

Measurements on the ceiling with horizontal slat angles showed an increased illuminance level at 3 m (37%), while it was reduced at the back (2-13%), compared to the reference room (Figure 6.44). Upward tilted slat angles of -30° and -45° reduced the illuminance level at 3-5.4 m by 24-43%, while it was almost unchanged at the window perimeter. Manual luminance measurements on the ceiling in three different position are shown in Table V.36. The luminance ratio for the horizontal slat angle was 10:1 between 0.6 m and 5.4 m, while the ratio was approximately 3:1 in the reference room. Downward tilted slats angles of +30° and +45°, caused the direct sun to be reflected to the ceiling, increasing luminance ratio to roughly 30:1 and 15:1, respectively.

Table V.36 Luminance measurements on the ceiling in three different position with reflective Venetian blinds and the reference room.

Reflective Venetian blinds Ceiling	**Daylight Laboratory**			**Reference Room**		
	0.6 m [cd/m^2]	3.0 m [cd/m^2]	5.4 m [cd/m^2]	0.6 m [cd/m^2]	3.0 m [cd/m^2]	5.4 m [cd/m^2]
VB 0°	1500	400	150	390	260	160
VB -30°	720	420	150	380	260	150
VB -45°	590	400	140	360	250	150
VB -60°	300	250	100	350	250	150
VB +30°	2650	300	100	350	270	160
VB +45°	1600	370	100	350	280	170
VB +60°	920	270	60	350	280	180

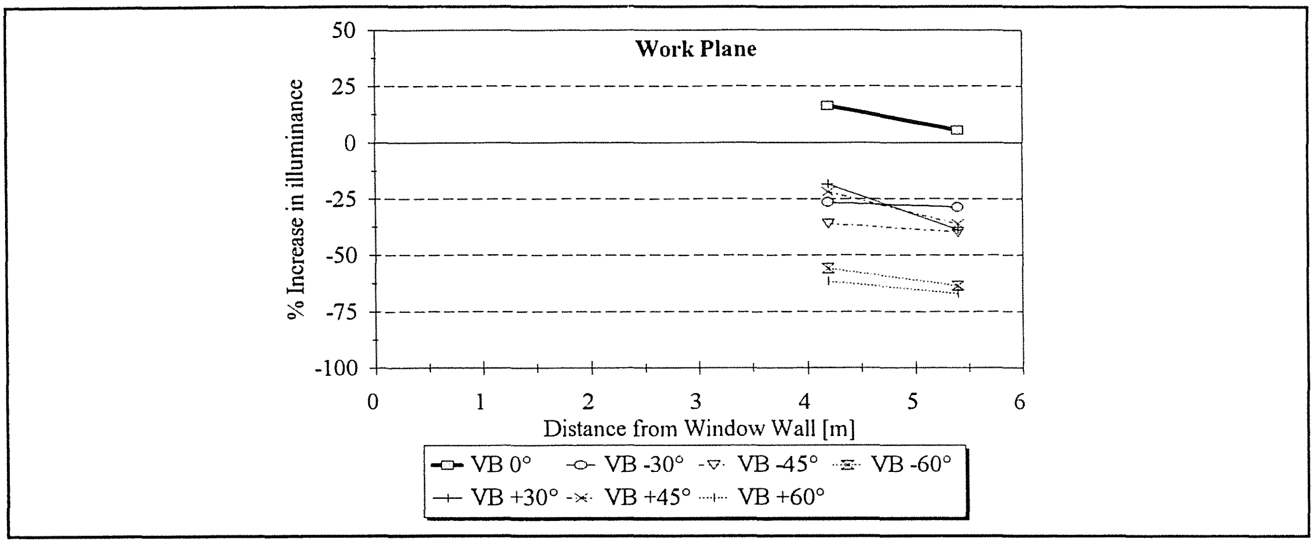


Figure 6.43 Direct Sun: The percentage change in illuminance level on the Work Plane for reflective Venetian blinds (all slat angles) relative to the reference room.

Table V.37 Average illuminance level [lux] on the Work Plane for reflective Venetian blinds (all slat angles), adjusted to exterior vertical sky illuminance (70.000 lux).

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
VB Reflective Large: 0° [lux]	8800	> 4000	> 4000	> 4000	940	550
VB Reflective Large: -30° [lux]	> 20000	> 4000	> 4000	> 4000	670	440
VB Reflective Large: -45° [lux]	> 20000	> 4000	> 4000	> 4000	570	370
VB Reflective Large: -60° [lux]	3170	2110	> 4000	2280	390	220
VB Reflective Large: +30° [lux]	5740	> 4000	3200	1450	700	360
VB Reflective Large: +45° [lux]	2970	2360	1910	1090	650	370
VB Reflective Large: +60° [lux]	1190	1020	860	520	320	190

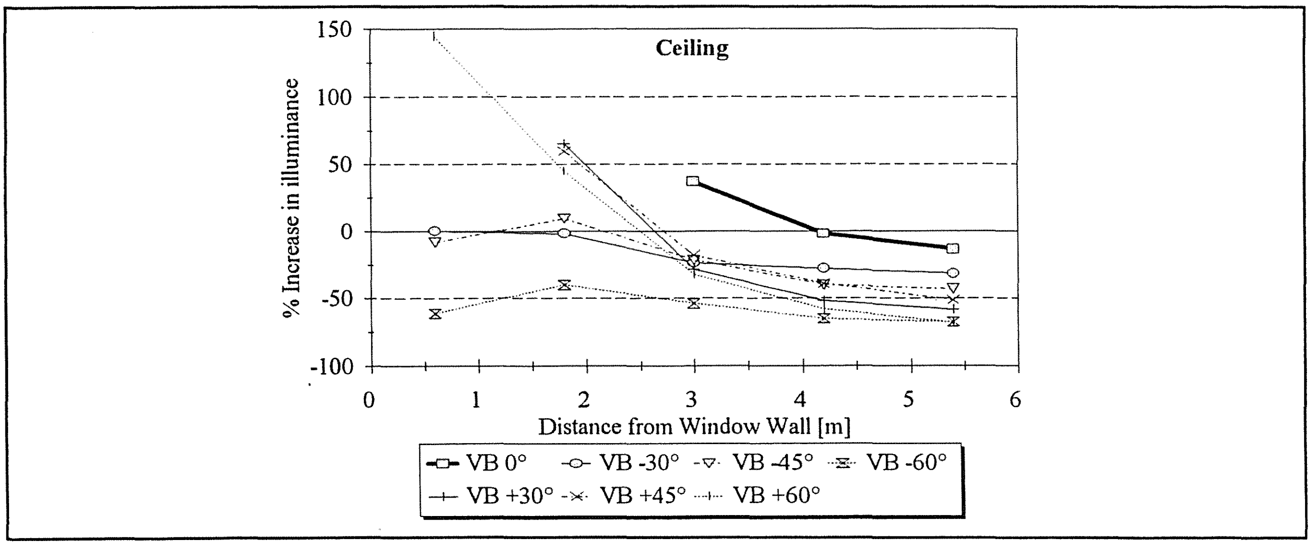


Figure 6.44 Direct Sun: The percentage change in illuminance level on the Ceiling for reflective Venetian blinds (all slat angles) relative to the reference room.

Table V.38 Average Illuminance level [lux] on the Ceiling for reflective Venetian blinds adjusted to exterior vertical sky illuminance (70.000 lux).

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
VB Reflective Large: 0° [lux]	> 4000	> 4000	1440	810	540
VB Reflective Large: -30° [lux]	1510	1440	960	630	380
VB Reflective Large: -45° [lux]	1320	1530	950	520	410
VB Reflective Large: -60° [lux]	530	800	540	300	180
VB Reflective Large: +30° [lux]	> 4000	2100	810	400	240
VB Reflective Large: +45° [lux]	> 4000	1920	890	500	280
VB Reflective Large: +60° [lux]	2920	1670	710	350	200

6.2.6 White Venetian blinds: Clear Sky with direct sun

The white coloured Venetian blinds (diffuse slat surface), showed similar illuminance levels on the work plane as the large scaled, reflective Venetian blinds. Table V.40 and Table V.41 show the adjusted interior illuminance levels in lux on the work plane and the ceiling, respectively. The horizontal and upward tilted slat angles caused the detectors at 1.2-1.8 m from the window wall on the work plane to be in direct sun or beyond the output range of the detectors.

Figure 6.45 shows that all slat angles caused insignificant variations in the reduced work plane illuminance level at 3-5.4 m, compared to the reference room. The smallest reductions were provided by the horizontal slat angles, causing the work plane illuminance level to be reduced by 27%. With the blinds upward (VB -30° and VB -45°), the illuminance level on the work plane was reduced by 31% and 46%, respectively. Excluding direct sunlight partly or completely, caused the downward tilted slat angles to reduce the relative work plane illuminance level at the back (3-5.4 m) by roughly 15-25% compared to the equally inverted slat angles. However, the downward tilted blinds reflected the incident light diffusively which affected the luminance level on the ceiling in the front half of the room (Table V.39).

Measurements on the ceiling with horizontal slat angles showed a reduced illuminance level at 1.8-5.4 m by 3-42%, compared to the reference room (Figure 6.46). The upward tilted slat angle of -30°, corresponding to the horizontal slat angle, increased the illuminance level at 3-5.4 m, so that the reduction was now only 32%. Luminance measurements on the ceiling in three different position are shown in Table V.36. The luminance ratio for the horizontal slat angle between 0.6 m and 5.4 m was 13:1, while the ratio was roughly 3:1 in the reference room. Downward tilted slats angles of +30° and +45° caused the direct sun to be reflected to the ceiling, increasing luminance ratio to 22:1 and 17:1, respectively. The luminance ratios show a significant difference between closing the blinds either upward (6:1) or downward (20:1), since the upward tilted blind transmitted some light directly through the blind, while the downward tilted blind reflected "all" incident light to the exterior and the ceiling.

Table V.39 Luminance measurements on the ceiling in three different position with the white coloured Venetian blinds and the reference room.

White Venetian blinds Ceiling	Daylight Laboratory			Reference Room		
	0.6 m [cd/m^2]	3.0 m [cd/m^2]	5.4 m [cd/m^2]	0.6 m [cd/m^2]	3.0 m [cd/m^2]	5.4 m [cd/m^2]
VB 0°	1400	380	110	430	300	150
VB -30°	880	450	140	430	320	150
VB -45°	770	350	110	430	290	150
VB -60°	450	200	80	420	280	140
VB +30°	1700	200	80	420	290	150
VB +45°	1200	180	70	400	270	150
VB +60°	780	120	40	390	270	140

6.2.7 Black Venetian blinds: Clear Sky with direct sun

The black coloured Venetian blinds showed the minimum "possible" incident light reflected to the interior (Figure 6.47). Table V.42 and Table V.43 show the adjusted interior illuminance level in lux on the work plane and the ceiling, respectively. Figure 6.47 shows the reduced work plane illuminance level at 3-5.4 m, where the reduction with the horizontal slat angle was 45-50% compared to the reference room. Table V.42 shows the unacceptable interior illuminance levels of the black Venetian blinds especially caused by the downward tilted slat angle resulting in a work plane illuminance level at the back, varying from 20-110 lux (4.2 m) to 10-70 lux (5.4 m).

Measurements on the ceiling showed that the smallest reductions were caused by the upward tilted blinds of VB -30°, giving an illuminance level reduced by 34-45% (Figure 6.48). The horizontal slat angle reduced the illuminance level by approximately 50%. The measured values at the back, with the downward tilted slat angles are so low that the differences are of the same order as the accuracy of the detectors. Table V.44 shows that the luminance ratio was roughly 7:1 for the horizontal and the upward tilted slat angles. Downward tilted slat angles showed a luminance ratio of approximately 15:1.

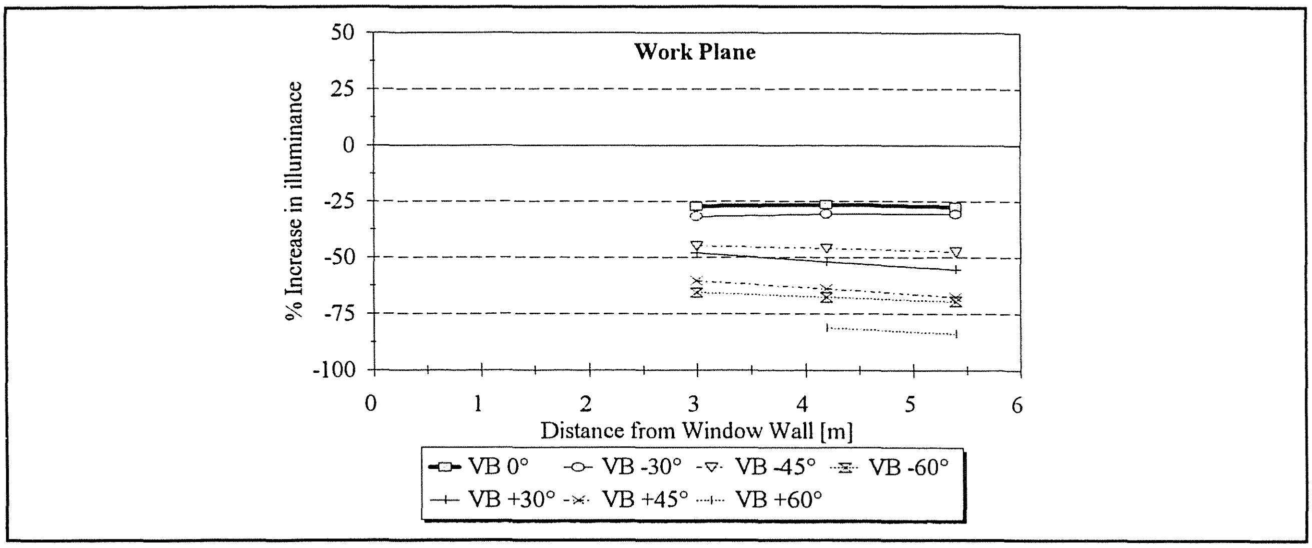


Figure 6.45 Direct Sun: The percentage change in illuminance level on the Work Plane for the white coloured Venetian blinds (all slat angles) relative to the reference room.

Table V.40 Average Illuminance level [lux] on the Work Plane for white coloured Venetian blinds adjusted to exterior vertical sky illuminance (70.000 lux).

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
VB White: 0° [lux]	17720	> 4000	2560	1350	800	470
VB White: -30° [lux]	11870	> 4000	> 4000	1250	750	450
VB White: -45° [lux]	6680	> 4000	> 4000	970	570	340
VB White: -60° [lux]	4040	> 4000	> 4000	590	340	200
VB White: +30° [lux]	4570	2720	2280	870	470	270
VB White: +45° [lux]	2790	1930	1340	650	370	210
VB White: +60° [lux]	1300	890	650	330	180	100

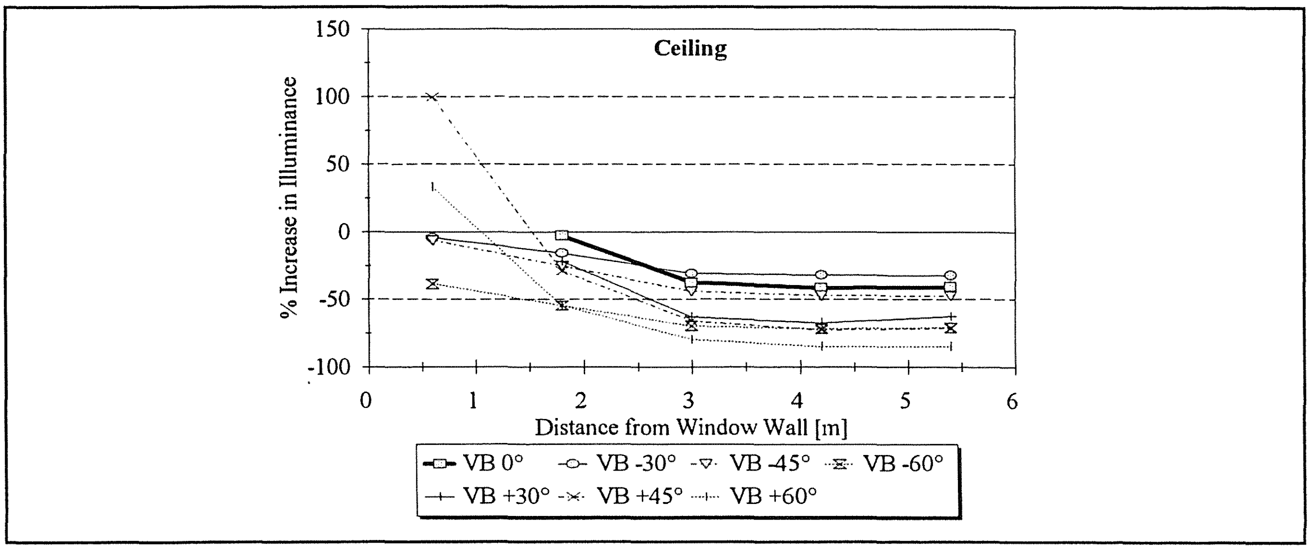


Figure 6.46 Direct Sun: The percentage change in illuminance level on the Ceiling for the white coloured Venetian blinds (all slat angles) relative to the reference room.

Table V.41 Average Illuminance level [lux] on the Ceiling for white coloured Venetian blinds adjusted to exterior vertical sky illuminance (70.000 lux).

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
VB White: 0° [lux]	> 4000	2100	1070	610	330
VB White: -30° [lux]	2050	1780	1180	720	380
VB White: -45° [lux]	1920	1510	900	540	300
VB White: -60° [lux]	1210	880	490	290	180
VB White: +30° [lux]	> 4000	1470	570	310	190
VB White: +45° [lux]	3720	1280	510	270	170
VB White: +60° [lux]	2320	760	280	140	80

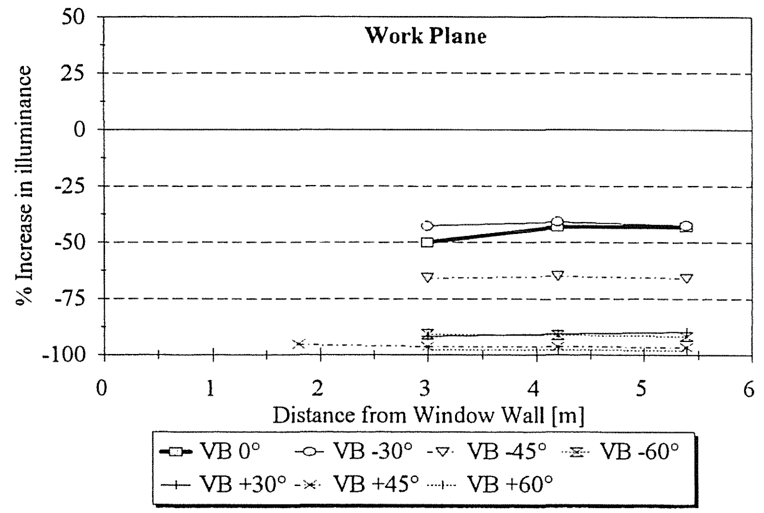


Figure 6.47 Direct Sun: The percentage change in illuminance level on the Work Plane for the black coloured Venetian blinds (all slat angles) relative to the reference room.

Table V.42 Average Illuminance level [lux] on the Work Plane for the black coloured Venetian blinds adjusted to exterior vertical sky illuminance (70.000 lux).

Work Plane	**0.6 m**	**1.2 m**	**1.8 m**	**3.0 m**	**4.2 m**	**5.4 m**
VB Black: 0° [lux]	12090	2010	1800	1080	660	380
VB Black: -30° [lux]	> 20000	3390	2540	1230	690	390
VB Black: -45° [lux]	> 20000	2280	1590	730	410	230
VB Black: -60° [lux]	3500	2520	480	190	100	60
VB Black: +30° [lux]	350	690	280	170	110	70
VB Black: +45° [lux]	130	140	130	70	40	20
VB Black: +60° [lux]	90	90	80	50	20	10

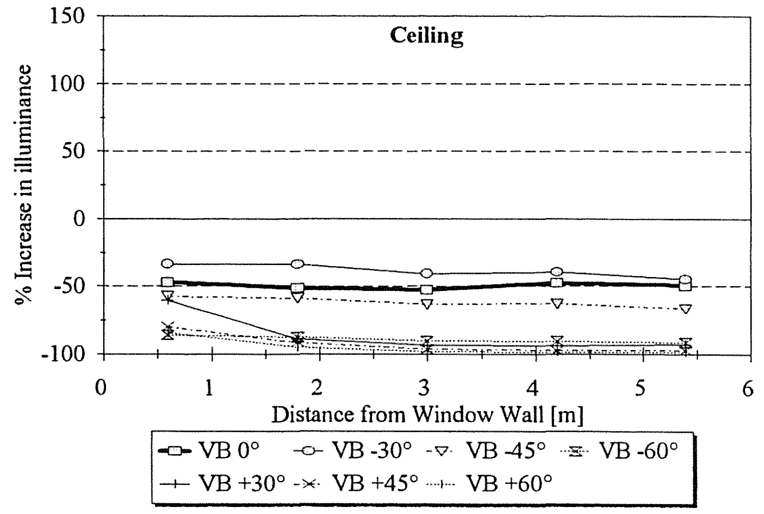


Figure 6.48 Direct Sun: The percentage change in illuminance level on the Ceiling for the black coloured Venetian blinds (all slat angles) relative to the reference room.

Table V.43 Average Illuminance level [lux] on the Ceiling for the black coloured Venetian blinds adjusted to exterior vertical sky illuminance (70.000 lux).

Ceiling	**0.6 m**	**1.8 m**	**3.0 m**	**4.2 m**	**5.4 m**
VB Black: 0° [lux]	1500	1300	890	520	270
VB Black: -30° [lux]	1830	1730	1120	630	310
VB Black: -45° [lux]	1160	1060	690	390	190
VB Black: -60° [lux]	370	310	180	100	35
VB Black: +30° [lux]	1010	270	120	70	40
VB Black: +45° [lux]	500	200	60	30	20
VB Black: +60° [lux]	380	120	30	20	10

Table V.44 Luminance measurements on the ceiling in three different position with black Venetian blinds and the reference room.

Black Venetian blinds Ceiling	Daylight Laboratory			Reference Room		
	0.6 m [cd/m^2]	3.0 m [cd/m^2]	5.4 m [cd/m^2]	0.6 m [cd/m^2]	3.0 m [cd/m^2]	5.4 m [cd/m^2]
VB 0°	410	190	60	450	350	120
VB -30°	700	300	85	450	350	130
VB -45°	460	200	50	450	350	140
VB -60°	180	75	25	460	350	150
VB +30°	190	40	15	470	350	150
VB +45°	160	25	10	470	340	150
VB +60°	130	15	8	450	330	150

6.2.8 Subjective evaluation of the Venetian blinds

The interior "quality" when using the Venetian blinds was assessed by luminance and illuminance measurements together with subjective evaluations of the performance and modifications to the interior environment. The assessments, conducted from a sitting or standing position, were concentrated at glare problems and the luminance distributions in the interior. Assessment of glare problems in the interior was supplemented with measurements of the sky luminance and the interior adaptation luminance for a singular measuring position towards the window from the middle of the room (3 m).

Figure 6.49 Interior photograph of the Venetian blinds with horizontal slat angle (VB 0°), showing the view-out function at a distance approximately 2 m from the window.

Subjective assessments of the exterior view were interfered by the completely or partly directionally obstructed exterior view, since the different slat angles and the distance between the slats always reduced the outside view. Horizontal blinds (VB 0°) display the "non-screen" pass-through view of both the sky and exterior ground, while downward tilted slat angles enhance ground view and upward tilted slat angles enhance sky view. The main deficiencies experienced with the Venetian blinds were that they occasionally produced an annoying "visual noise" in the view, caused by the figure/background confusion. The visual discomfort was caused by the confusion in sorting out the interesting visual signal of the view from the interruptive "visual noise" generated by the blinds, depending on the slat angle. The blinds in the horizontal position reduced the figure/background confusion since the view stripe was more interesting and the blinds' structure showed a diminishing interference of view. Tilting the

Venetian blinds detracted the exterior view, and generated both an increased figure/background confusion but also a confusion of colour judgements of the leaves on the trees in front of the daylight laboratory and the opposite, red coloured building construction (bricks). This confusion was experienced, but not always replicated, when the sky was overcast and the slat angles tilted 30° and 45° degrees upward, allegedly caused by the luminance level of the slat and the reduced adaptation luminance, thus interfering the colour sensitivity of the eye. Direct sunlight striking the slats disrupted the view since the sun caused extremely intolerable bright lines on the slats, exceeding 100.000 cd/m^2.

Figure 6.50 Interior photograph of the Venetian blinds with upward tilted slat angle (VB −30°), showing the view-out function at a distance approximately 2 m from the window.

Figure 6.51 Interior photograph of the Venetian blinds with downward tilted slat angle (VB +30°), showing the view-out function at a distance approximately 2 m from the window.

An acceptable view at 3 m from the window and with the blinds in a horizontal position, was only experienced for the large and the medium scaled blinds. The small scaled, reflective Venetian blinds, intended for use between two layers of glazing, increased the visual discomfort even with the slats in the horizontal position. The small distance between the slats (13 mm) enhanced the problems of obstructed exterior view, the figure/background confusion and the discrepancies of colour jugdements.

A bright overcast sky caused glare problems with the blinds in the horizontal position, because of the increased luminance level at the slats and the reduced interior adaptation luminance. Furthermore, the horizontal slat position maintained almost unchanged exposure to the bright sky viewed through the blinds. Increasing the visibility of the sky by tilting the blinds upward enhanced the magnitude of glare, even if the interior adaptation luminance at the front end of the room was simultaneously raised. Depending on the distance of observation, downward tilted slat angles shaded the visible sky and reduced glare problems. Problems with reflected glare arose, especially in a standing position, because direct sunlight and bright skylight were reflected off the slat surface, directly into the field of view. The reflective Venetian blinds caused a similar effect as described with the reflective light shelves, especially on a clear day with direct sun. Subjective dissatisfaction was primarily caused by the reflective blinds systems, but also the white diffuse Venetian blinds gave similar but less significant problems of direct glare. The magnitude of reflected glare was severe and intolerable since direct sunlight reflected off the slats caused severe reduction of the visibility and tears in one's eyes, even when viewed from a position almost 6 m from the window, looking straight at the blinds. Changing the position of observation away from the direct reflected sunlight did not reduce the disabling effect since the luminance and intensity of the slats were unchanged. Reflected sunlight "pictured" in the interior created additional visual distractions, since the Venetian blinds reflected bands of light at particular spatial frequencies on the ceiling and the adjacent wall. All these visual discomfort problems were reduced when the slats were tilted downward and by using a diffuse slat surface.

Assessment of glare problems in the interior was supplemented with measurements of the window luminance, the interior adaptation luminance at a singular position in the middle of the room (3 m). The luminance measurements of the window were conducted at 9 reference points by subdividing the window into 3 by 3 rectangles. Table V.45 shows the variation of the luminance measurements of the window for 3 selected Venetian blinds on a clear day with direct sun in October. The extremely intolerable bright lines of direct sunlight striking the slats (> 100.000 cd/m^2) are not shown.

Table V.45 Luminance measurements on the window with three Venetian blinds.

Luminance measurements Window	Large scaled reflective Venetian blind [cd/m^2]	Medium scaled white Venetian blind [cd/m^2]	Medium scaled black Venetian blind [cd/m^2]
VB 0°	2100-16000	1200-21000	1000-17000
VB -30°	2000-16000	2200-15000	200-10000
VB -45°	4000-13000	3400-8500	100-6600
VB -60°	2500-15000	1500-5000	20-270
VB +30°	3000-20000	4000-12000	200-7000
VB +45°	5000-20000	3000-5500	30-1500
VB +60°	1900-12000	600-3600	10-50

The intentions of the measurements of Venetian blinds were to investigate their ability to increase daylight penetration while providing the interior with a shading device for direct sunlight and bright sky luminances when needed. Only the large scaled, reflective Venetian blinds in a horizontal position fulfilled the intentions of increased illuminance level at the back on a clear day with direct sun in October. However, the blinds caused a window luminance level above 10.000 cd/m^2, which will often be experienced as unacceptable and this will exclude the large scaled, reflective Venetian blinds as a shading device. Table V.45 shows that only the white coloured Venetian blinds, with downward tilted slat angles of +45° and +60°, caused an efficient and acceptable shading of the direct sun, satisfying one of the intentions. The black coloured Venetian blinds are excluded as a daylight system because of the unacceptably low interior illuminance levels.

6.3 Performance of a white diffuse curtain

Curtains are the most traditional "shading device" to partly or totally block direct sun and diffuse skylight. The interior curtain was made of a white, semi-transparent material with a shading coefficient of 0.45, to allow diffuse transmittance of incident light.

6.3.1 Diffuse curtain: Overcast Sky

The interior diffuse curtain caused a reduced illuminance level on the work plane and on the ceiling compared to the reference room. The work plane illuminance level was reduced by 63-80%, least at the back (4.2-5.4 m) (Figure 6.52).

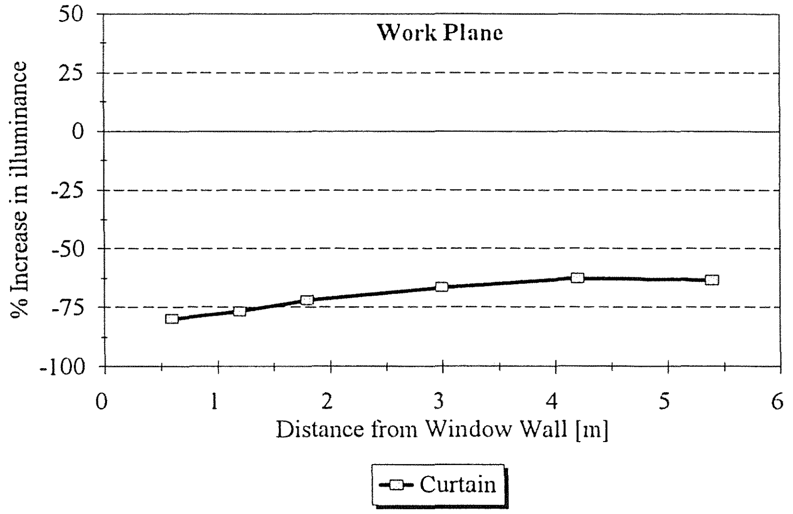


Figure 6.52 Overcast Sky: The percentage change in illuminance level at the Work Plane for white diffuse Curtain relative to a room with traditional window.

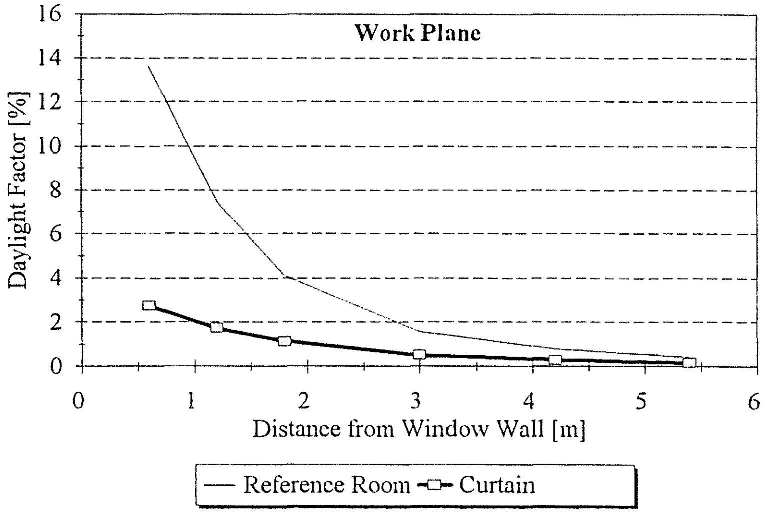


Figure 6.53 Overcast Sky: The daylight factor [%] on the Work Plane for white diffuse Curtain relative to the reference room.

Table V.46 Average Daylight Factor [%] on the Work Plane for a white diffuse Curtain compared to the reference room.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	13.6	7.5	4.1	1.6	0.8	0.5
Diffuse Curtain	2.7	1.7	1.1	0.5	0.3	0.2

Figure 6.53 shows the daylight factors on the work plane for the diffuse curtain (Table V.46), where a daylight factor of 2% is achieved at a distance of only about 1 m from the window wall.

Measurements on the ceiling surface showed that the diffuse transmission through the curtain slightly reduced the illuminance level by 8-15% at 0.6-1.8 m (Figure 6.54).

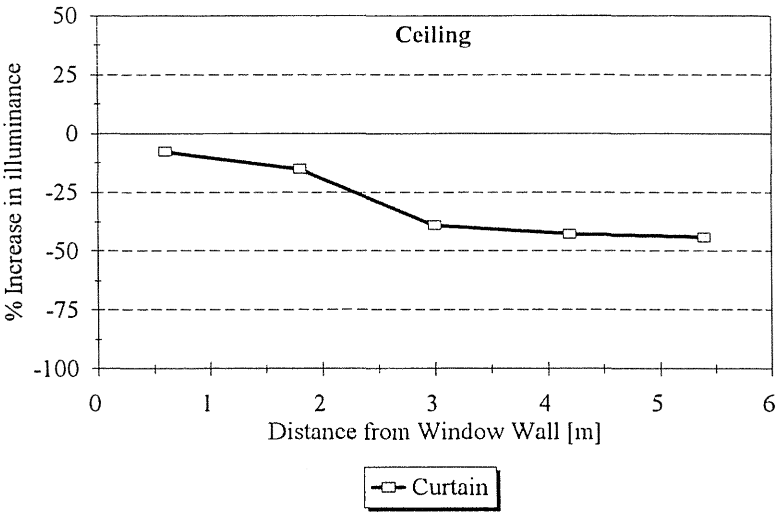


Figure 6.54 Overcast Sky: The percentage change in illuminance level on the Ceiling for white diffuse Curtain relative to the reference room.

Table V.47 Average Daylight Factor [%] on the Ceiling for a white diffuse Curtain compared to the reference room.

Ceiling	0.6 m	1.8 m	3.0 m	4.2 m	5.4 m
Reference Room	1.6	1.1	0.7	0.4	0.3
Diffuse Curtain	1.5	0.9	0.4	0.2	0.1

6.3.2 Diffuse curtain: Clear Sky with direct sun

Measurements of the interior diffuse curtain with direct sun were conducted in October 1994 with the solar azimuth angle perpendicular to the window. The interior illuminance levels were also adjusted relative to an exterior vertical sky illuminance of 70.000 lux (Table V.49).

The diffuse curtain reduced the work plane illuminance level at the back by 13-32%, highest at 5.4 m (Figure 6.55). Measurements on the ceiling surface showed that the illuminance level at 1.8 m was increased by 105%, due to the semi-transparent material used and the diffusively transmitted sunlight (Figure 6.56). Table V.48 shows the luminance measurements on the ceiling, where the luminance ratio was roughly 10:1 between the window perimeter zone (0.6 m) and at the back (5.4 m). The reference room showed a luminance ratio of approximately 1:1.

Table V.48 Luminance measurements on the ceiling at three different positions (October) with interior diffuse curtain and the reference room.

Diffuse Curtain: Ceiling	Daylight Laboratory			Reference Room		
	0.6 m [cd/m²]	3.0 m [cd/m²]	5.4 m [cd/m²]	0.6 m [cd/m²]	3.0 m [cd/m²]	5.4 m [cd/m²]
Curtain - Oct.	1250	400	140	350	350	310

6.3.3 Subjective evaluation of the white diffuse curtain

Assessments of glare problems in the interior were supplemented with luminance measurements of the window. Averaged luminance measurements of the windows with the white diffuse curtain resulted in a luminance level of approximately 10.000 cd/m^2 on a clear day in October. The diffuse curtain caused increased glare problems since the interior adaptation luminance was reduced and the view to the outside was eliminated.

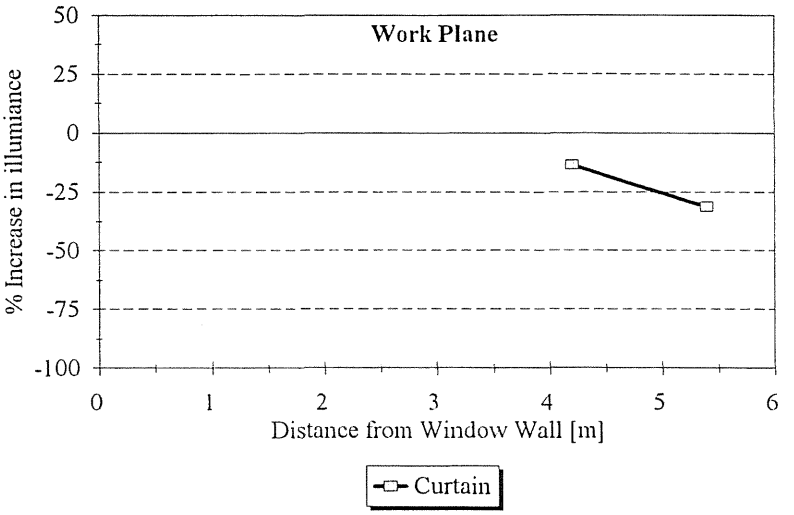


Figure 6.55 Direct Sun: The percentage change in illuminance level on the Work Plane for a white diffuse Curtain relative to the reference room.

Table V.49 Average Illuminance level [lux] on the Work Plane for a white diffuse curtain adjusted to exterior vertical sky illuminance (70.000 lux).

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
Diffuse Curtain	6420	3960	2830	1990	660	380

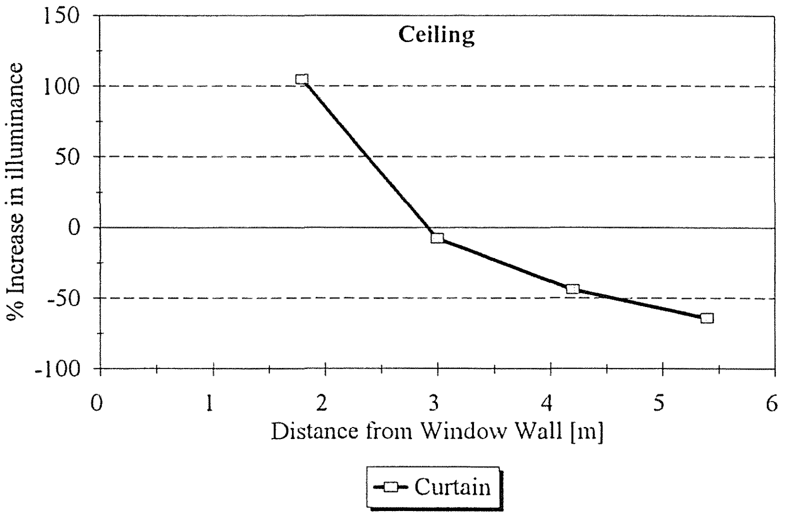


Figure 6.56 Direct Sun: The percentage change in illuminance level on the Ceiling for a white diffuse Curtain relative to the reference room.

Table V.50 Average Illuminance level [lux] on the Ceiling for a white diffuse curtain adjusted to exterior vertical sky illuminance (70.000 lux).

Ceiling	0.6m	1.8m	3.0m	4.2m	5.4m
Diffuse Curtain	3420	2030	900	490	320

7. Tools for Daylighting Design and Analysis

In designing energy efficient buildings it is essential to use tools that can simulate the complex and dynamic behaviour of buildings under realistic conditions of use and operation. Computer simulations may save the architect and engineer time and effort and at the same time offer increased information about the physical impact of the design decisions. However, most daylighting computer tools are not yet adequate regarding good daylighting design in the view of the qualitative aspect. Traditional daylight calculations lack the possibility of displaying the dynamic variation of daylight in real buildings during the day and over the year. Daylighting computer tools are predominantly concerned with the physical illuminance and luminance levels using a variety of approaches, none of which are related neither to the psychophysical nor psychological aspects of lighting. The current revolution in computer technology will inevitably improve the tools' capabilities and accuracy in predicting not only the physical quantities, but also the psychophysical aspects of daylight in the interior.

This chapter describes selected daylight design tools, of which some are used to analyse the consequences of replacing artificial lighting with daylight when this is sufficient. To take full advantage of the potential energy savings, it is necessary to perform an integrated analysis of natural daylight, artificial light and light control strategies with the energy and thermal performance of buildings [Christoffersen 1992 a-b].

7.1 BRS daylight protractors

BRS daylight protractors, first produced in 1946, are widely used and accepted as a relatively accurate technique for estimation of interior illuminance levels and/or a daylight factors for two overcast sky luminance distributions [Longmore 1968, Hopkinson 1966, Löfberg 1987]. The sky luminance distribution, either the uniform sky or the CIE standard overcast sky, assumes the atmospheric hemisphere to have an isotropic sky intensity distribution. The daylight factor DF at a reference point (horizontal surface), is received from three components (see Figure 7.1):

- directly from the sky is *the sky component SC*
- after reflection from external surfaces is *the externally reflected component ERC*
- after reflection from internal surfaces is *the internally reflected component IRC*

$$\textit{Daylight Factor DF} = SC + ERC + IRC \qquad 7.1$$

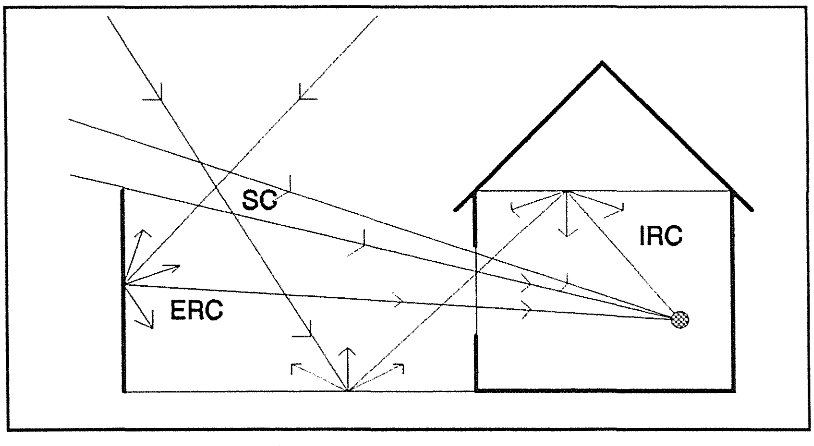


Figure 7.1 Illustration of daylight received on a horizontal surface in the interior by its components SC, ERC and IRC.

Daylight received in the interior for a reference point (horizontal surface), directly from a sky of assumed or known luminance distribution (isotropic) and/or from the surroundings, is a function of the angle of incidence and the solid angle subtended from the interior point of the exterior visible sky seen through the window. This is the basis for the use of the BRS Protractors (see Figure 7.2).

7.1.1 Sky component SC

Figure 7.2 illustrates the principle when using protractors. The upper scale determines the sky component from an infinitely long window, while the lower scale corrects for the finite length of a window. From a predefined interior reference point along the reference plane, the sky component can be determined by drawing the line of sight to the upper and lower edges of the window, determining the visible patch of sky and external surroundings. The difference between the two readings defines the primary sky component for an infinitely long window. To compensate for light transmission loss due to the angle of incidence (single glazing), an average angle of elevation is introduced. A correction factor due to finite window length (illustrated at the bottom of Figure 7.2) can be decided by projecting the line of sight to the vertical edges of the window, thus defining the width of the visible sky patch seen from the reference point.

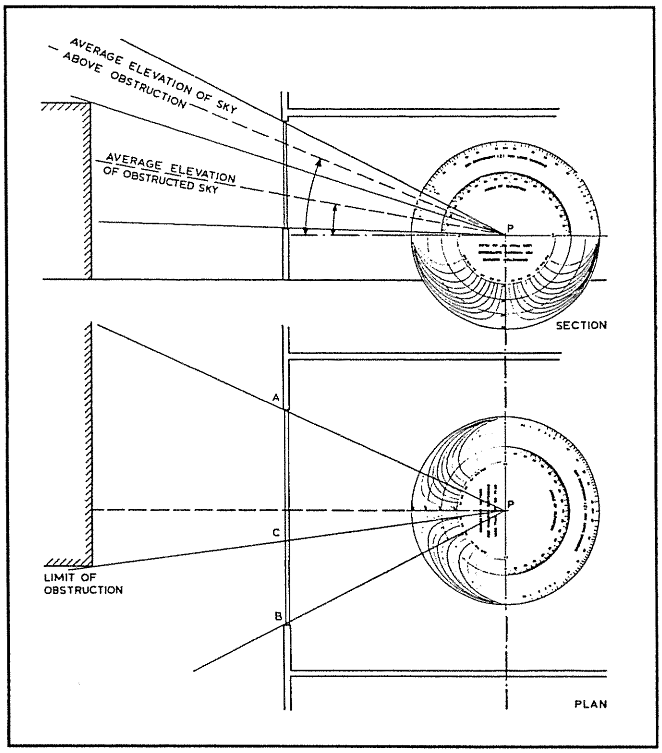


Figure 7.2 Protractors to determine the sky component compensating for obstruction of limited length opposite a window [reprinted from Longmore 1968].

Instead of using the protractors to estimate the sky component for a vertical window, it is possible to define an analytical solution as expessed by the integral in eq. 7.2. This equation can be used for any sky luminance distribution to decide the amount of daylight illuminance at a reference point P. Figure 7.3 shows the reference point P on a horizontal plane and a rectangular vertical window with its sill height positioned at the same plane. The illuminance level E_p (in lux) is found by integrating eq. 7.2 over the area of the window corresponding to the visible sky seen through the window [Littlefair 1986]:

$$E_p = \int_0^{\Phi} \int_0^{\theta} L(\theta,\Phi) \cdot \sin\theta \cdot \cos\theta \cdot d\theta \cdot d\Phi \qquad 7.2$$

where $L(\Theta,\Phi)$ [cd/m^2] is the sky luminance distribution
Θ and Φ are the altitude and azimuth angle

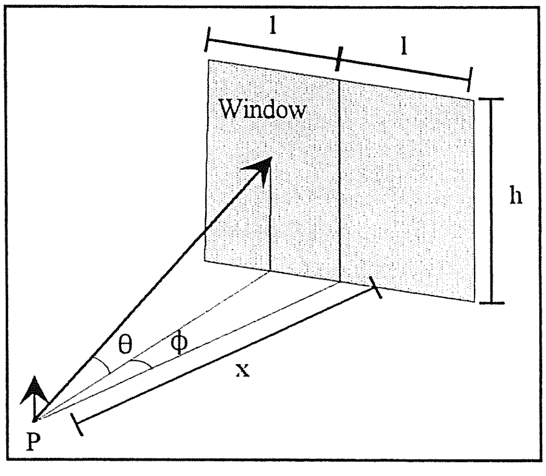


Figure 7.3 Determine SC in point P for a rectangular aperture in a vertical plane.

The analytical solution of eq. 7.2 for correct view factor (vertical window) measured from any interior reference point has a view of the sky described by Θ and Φ [Hopkinson 1966]. Transmission loss due to the glazing and angle of incidence are not incorporated. The sky component at a reference point P for a rectangular aperture in a vertical plane for a uniform sky (eq. 7.3) and a CIE standard overcast sky (eq. 7.4), later used to verify other daylight design tools, is given by [Baker 1993, Compagnon 1994]:

Uniform sky:

$$E_p(l,h,x) = L_z \cdot \left[\arctan\left(\frac{l}{x}\right) - \frac{x}{\sqrt{h^2 + x^2}} \cdot \arctan \frac{l}{\sqrt{h^2 + x^2}} \right] \qquad 7.3$$

CIE standard overcast sky:

$$\begin{aligned} E_p(l,h,x) &= \frac{3 \cdot L_z}{7} \cdot \left[\arctan\left(\frac{l}{x}\right) - \frac{x}{\sqrt{h^2 + x^2}} \cdot \arctan \frac{l}{\sqrt{h^2 + x^2}} \right] \\ &+ \frac{4 \cdot L_z}{7} \cdot \left[\arcsin \frac{l \cdot h}{\sqrt{l^2 + x^2} \cdot \sqrt{h^2 + x^2}} - \frac{l \cdot h \cdot x}{(h^2 + x^2) \cdot \sqrt{l^2 + h^2 + x^2}} \right] \end{aligned} \qquad 7.4$$

where L_z the zenith luminance [cd/m^2]
l is half the width of the window
h is the window height
x is the distance from the window to the reference point

7.1.2 Externally reflected component ERC

The externally reflected component ERC is light reaching the interior after reflection from an external surrounding, equivalent to the primary sky component modified by a fraction of the sky luminance otherwise received. Usually the fraction is 10% of the sky luminance of uniform distribution, while a CIE standard overcast sky produces a fraction of 10% due to the average sky luminance, or 20% of the luminance in the horizon obstructed by the external surrounding.

7.1.3 Internally reflected component IRC

The internally reflected component IRC is light received from the sky and ground-reflected and inter-reflected from internal reflecting surfaces. The contribution from the inter-reflected component depends on the reflection coefficient from walls, ceilings and floors relative to the amount of light received on these surfaces from the exterior ground plane, the sky and external obstructions. A commonly accepted equation determining the average IRC from a vertical window, is the BRE split flux equation (eq. 7.5) [Hopkinson 1966]. The equation divides the room into two zones determined by the mid-height of the vertical window where the upper zone receives daylight from the exterior ground, while the lower zone receives daylight from the sky and exterior obstructions. The value is higher at the window zone and lower further back in the room. The average IRC can be calculated by eq. 7.5.

$$Average\ IRC = \frac{0.85 \cdot W}{A\ (1 - R)}\ (C\ R_{fw} + 5\ R_{cw}) \qquad 7.5$$

where		
	W	glazing area
	A	interior surfaces including the window surface
	R	average reflection coeffient of interior surfaces including the window surface
	R_{fw}	the upper zone's average reflection coeffient of interior surfaces excluding the window surface
	R_{cw}	the lower zone's average reflection coeffient of interior surfaces excluding the window surface
	C	represents the impact of external obstructions

7.2 Description of the design tools in ADELINE

In 1990, the International Energy Agency (IEA) initiated TASK XII "Building Energy Analysis and Design Tools for Solar Applications". The task released in 1994 the computer tool Adeline (see Figure 7.4), an Advanced Daylighting and Electric Lighting Integrated New Environment [Adeline 1994 a-i]. Adeline is built around two daylight simulation programs, Superlite and Radiance, where the influence of daylight simulations (Superlite) can be combined (Superlink) with a thermal analysis program (DOE2.1, SUNCODE, tsbi3, TRNSYS). Adeline is a set of computer tools developed to produce accurate information about the indoor environment for traditional and complex fenestration systems, infinite room configurations, artificial lighting systems etc. The thermal analysis programs can be used for analysis of the combined effect of daylighting and artificial lighting on the energy balance and in thermal indoor climate [Christoffersen 1992a-b].

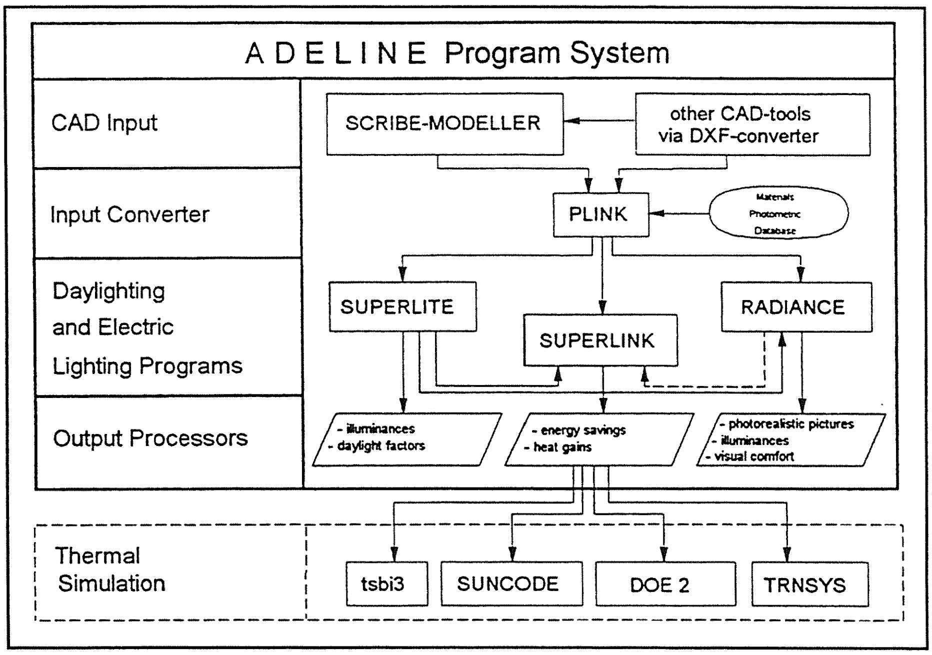


Figure 7.4 The various elements of Adeline and how they relate to one another [reprinted from Adeline 1994 a].

7.2.1 The CAD - program Scribe Modeller

Scribe Modeller is a CAD-system for modelling and evaluation of architectural designs, and the production of detailed two and three dimensional drawings (see Figure 7.5) [Adeline 1994 c]. It can be used to build any kind of shapes that can be defined by lines, edges, solids and planes. The program is designed for representing not only shapes and objects, but also their associated linecode attributed to each surface. In Adeline, Scribe Modeller is used solely to generate the skeleton input file for Superlite and Radiance.

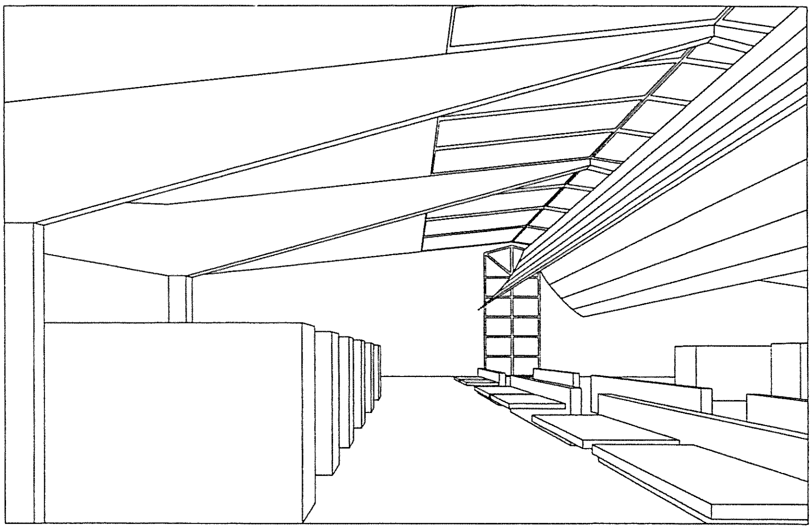


Figure 7.5 Example of the geometrical input using "Scribe Modeller" [reprinted from Adeline 1994 j].

7.2.2 The conversion program Plink

Plink is a link program which converts models designed by the Scribe Modeller into a Radiance scene description file or a Superlite input file [Compagnon 1992]. The program associates photometric and surface properties (material database) to the relevant linecode attributed to each surface by the Scribe Modeller. Plink also associates user-specified climatic data (CIE-skies) in order to produce "realistic" weather conditions. The material's database includes over 200 materials with opaque surfaces (e.g. concrete, bricks, wood, metal and properties of paints), transparent and translucent surfaces (e.g. glass and plastic materials), whose photometric properties have been measured on real samples (see Figure 7.6). The climatic inputs correspond to the solar contribution (direct only), clear skies (global/diffuse) and CIE standard overcast and uniform skies [Adeline 1994 d].

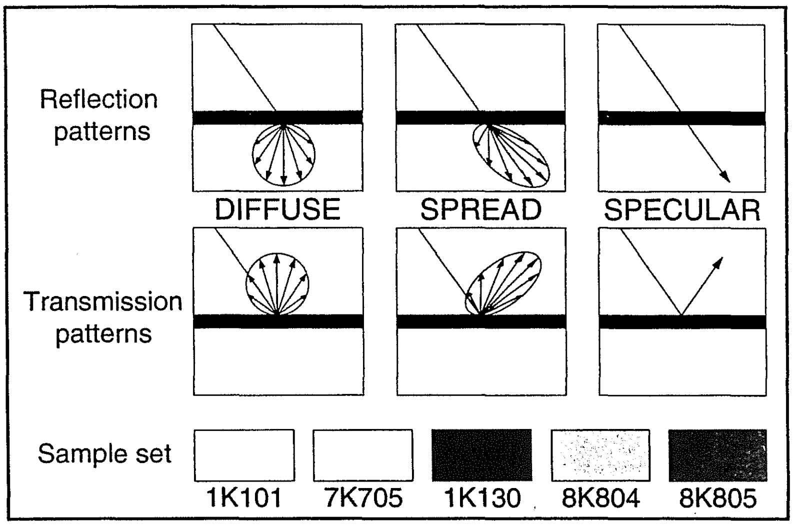


Figure 7.6 Example of the material photometry input using "Plink" [reprinted from Adeline 1994 j].

7.2.3 The daylight and lighting program Radiance

Radiance is in itself a package of sophisticated programs, which are able to simulate and display the quantity and quality of the complexity normally found in a real building design [Adeline 1994 b, h-i]. The desired output for which Radiance is tailored, visualises and produces realistic 3D colour images (see Figure 7.7) [Ward 1990 a-b]. Radiance was initially written to explore new and old techniques in lighting simulation, but as a research tool, it lacks many of the user-friendly features "normally" found in commercial software packages. Adeline has improved the input feasibilities for Radiance and at the same time excluded some possible input errors.

The "new" simulation technique used in Radiance is called backward ray-tracing [Ward 1988 b]. The idea of backward ray-tracing is based on a path of light tracked from its presumed destination to one or more sources, taking into account specular, semispecular, diffuse, refracting, translucent, transparent or coloured surfaces, and virtually any geometry. In this way, ray-tracing calculates luminances directly, which is ideal for the visualisation of illuminated spaces as an image, and is really just a collection of illuminance values [Ward 1988 a & 1991 & 1992 a-b].

The Radiance program is capable of simulating complex fenestration systems such as Venetian blinds, prismatic panels, reflectors and transparent insulation materials. Where architects and engineers earlier relied on scale measurements, Radiance can simulate the complex daylighting systems and offer several advantages. For example, Radiance provides control of boundary conditions, simulation of special systems which are difficult or impossible to model at reduced scale, measurements without disturbances at any location within the modelled space. It is also easy to change the design and photometric properties of materials.

The illuminance analysis of the light distribution in a building model can either be graphically displayed in two (Superlite) or three (Radiance) dimensions as iso-lux or iso-daylight-factors curves. The graphical display of the light penetration is powerful for estimating the performance of a daylighting system. The three dimensional display allows the designer to view the building from a selected view point and view direction or as a fish-eye lens. The program also allows "qualitative" analysis of the luminance distribution related to the eyes' sensitivity by identifying potential glare sources. This feature allows the user the ability to carry out a visual comfort analysis related to any view point and direction. Different glare indexes and Guth visual comfort probability can be calculated for a given rendered picture. A direct evaluation of user satisfaction can be obtained including optimal viewing direction for a given position of the observer.

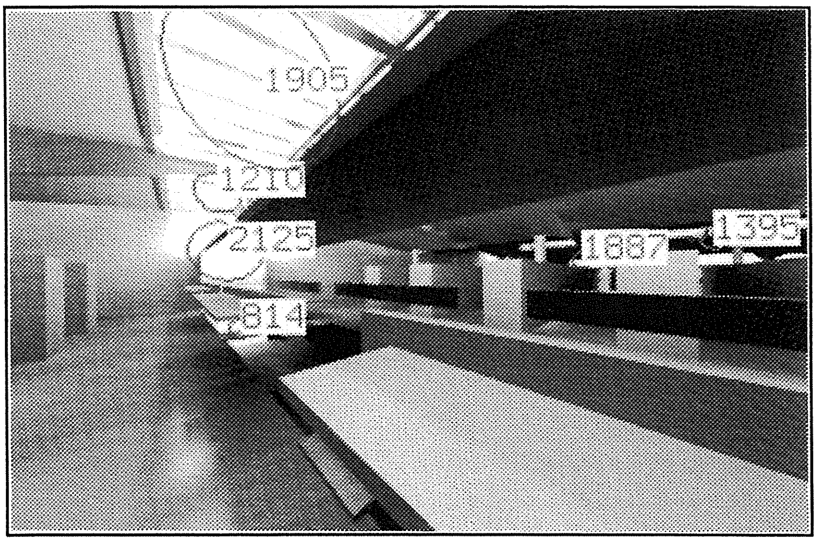


Figure 7.7 Example of visualisation of lighting conditions using Radiance [reprinted from Adeline 1994j].

7.2.4 The daylight program Superlite

Superlite is a daylight program, well validated, to predict daylight illuminance distribution for complex building geometries frequently found in the building environment, including several daylighting techniques and shading from external obstructions [LBL 1985, Adeline 1994 e]. The output from Superlite includes daylight factors, hourly illuminances on work-surfaces and/or luminances on indoor and outdoor surfaces (see Figure 7.8). The program treats only standard CIE clear or overcast skies and not real weather conditions. The calculation method is the flux transfer method including the Monte Carlo method for the direct illumination on external surfaces and numerical integration for direct illumination on indoor surfaces and work planes. Some of the major limitations to the Superlite program are: light reflected from exterior and interior is assumed to be perfectely diffuse, and complex fenestration systems such as Venetian blinds and specular light shelf etc. cannot be modelled.

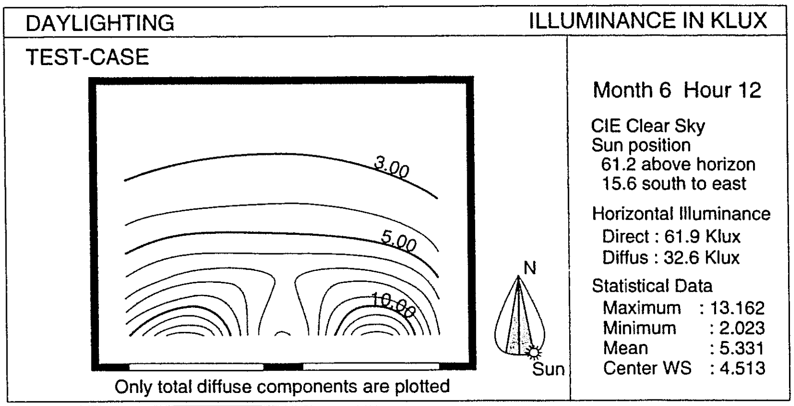


Figure 7.8 Example of the graphical presentation of the results in Superlite [reprinted from Adeline 1994 j].

Figure 7.9 shows the accuracy of Superlite relative to the analytical solution of the sky component for a finite rectangular window in a vertical plane for a uniform sky (eq. 7.3) and a CIE standard overcast sky (eq. 7.4). The results show negligible discrepancies in the amount of light from the sky throughout the interior depth [lux] for a rectangular window with dimensions $l \cdot h = 1.5 \cdot 1.5$ m^2, received 0.85 m above floor level.

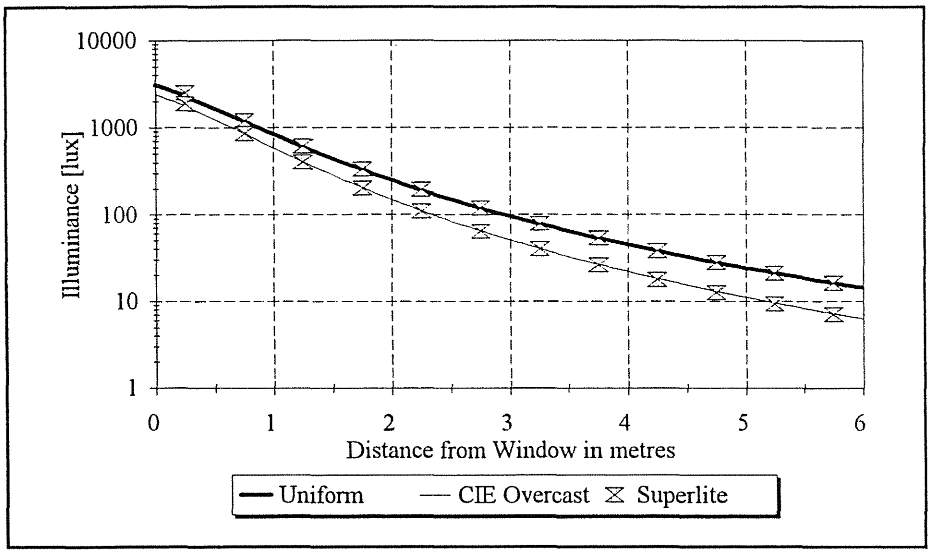


Figure 7.9 Comparison of Superlite's sky component relative to the analytical solution of the sky component for a finite rectangular window.

7.2.5 The link program Superlink

Superlink was developed by Fraunhofer Institute of Building Physics [Adeline 1994 f-g] to link a pure daylighting program, such as Superlite, to an energy program so that one could study the influence on the total energy balance of replacing electric lighting by daylighting (see Figure 7.10) [Christoffersen 1992 & 1993].

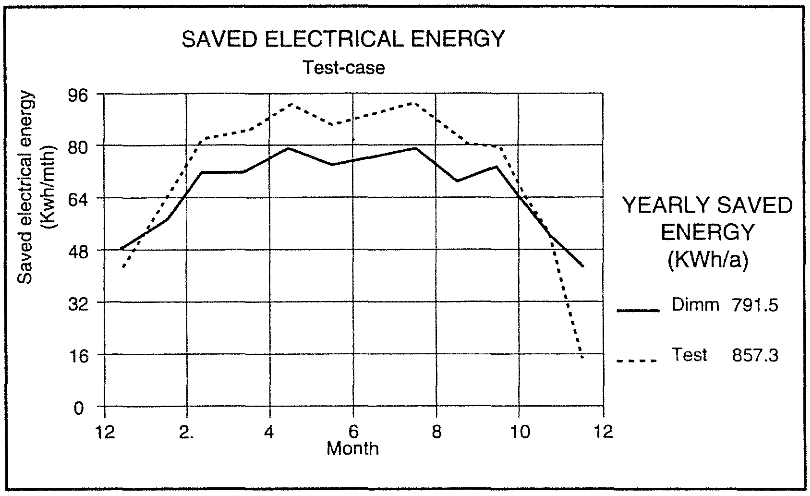


Figure 7.10 Example of the graphical presentation of the results in Superlink [reprinted from Adeline 1994 j].

Superlink uses an average sky model developed by [Aydinly 1981] to model the full range of actual sky conditions for several sun positions on the 15th of each month and for each hour of the day. The average sky model is intended to improve simulation accuracy for real weather conditions by replacing the shortcomings of the daylight factor methods [Littlefair 1990]. In Superlink, a given time step Δt (one hour) is simulated by Superlite for three CIE-standard sky conditions: overcast sky, clear sky without sun, and clear sky with sun. Superlink produces an average interior daylight illuminance frequency distribution model (Gaussian distribution) defined by the hourly sunshine probability (SSP) [Adeline 1994 f]. The interior daylight illuminance frequency distribution model uses the hourly sunshine probability derived from the Danish TRY weather data to approximate the work surface illuminance simulated by Superlite (three sky conditions). It is weighted relatively to the sunshine probability (SSP) separated into a sunny interval during Δt equal to SSP (composed of diffuse skylight and direct sunlight) and an interval without sun equal to 1-SSP (diffuse skylight only).

The average work surface illuminance is then compared to the required design illuminance and continuously recalculated for the energy needed from artificial lighting. This can be done for up to 25 reference points for different lighting control systems, such as continuous dimming control, stepped systems or manual control regulated by a probability function [Hunt 1980]. The hourly lighting energy consumption can then be used as internal heat gains in the linked thermal energy programs or simply as electric lighting energy consumption output.

Figure 7.11 shows an example of a file from Superlink, containing calculated data for power needed for artificial lighting (only the first 24 hours are shown). The columns define: hour, day, and month, and the power consumption in Watts. The values of the data file can be read directly from tsbi3, substituting the normal lighting as well as the lighting control for the general lighting [Johnsen 1993 & 1994]

```
 1     1     1        .000
 2     1     1        .000
 3     1     1        .000
 4     1     1        .000
 5     1     1        .000
 6     1     1        .000
 7     1     1        .000
 8     1     1     200.000
 9     1     1     114.888
10     1     1     158.050
11     1     1      71.803
12     1     1     158.050
13     1     1      70.803
14     1     1      70.803
15     1     1      30.960
16     1     1      30.960
17     1     1     200.000
18     1     1        .000
19     1     1        .000
20     1     1        .000
21     1     1        .000
22     1     1        .000
23     1     1        .000
24     1     1        .000
```

Figure 7.11 Example of data file from Superlink.

7.3 The thermal energy program tsbi3

tsbi3 is a commercial computer program, flexible and easy-to-use, developed by the Danish Building Research Institute [Johnsen 1993, 1994]. The program is widely used for research, education and by practitioners for building design and analysis of indoor environment and energy performance of complex building geometries, systems, and control functions. A building model contains data for the building site (climatic data), the building form (rooms or zones), the limiting surfaces for these zones, construction sub-surfaces, windows and doors, systems and loads in the building (operating conditions and schedules) and data describing patterns of operation and use. tsbi3 offers a flexible combination of systems and scheduled control strategies over time and is capable of simulating the dynamic interaction between the building structure and the systems. The building model is based on difference equations solved by an implicit method. tsbi3 has been thoroughly validated by analytical verification, comparative testing and through empirical methods. The models used have proved to provide reliable results in calculation of carefully measured test-houses, as well as in full simulation of commercial and institutional buildings with complex systems and control strategies.

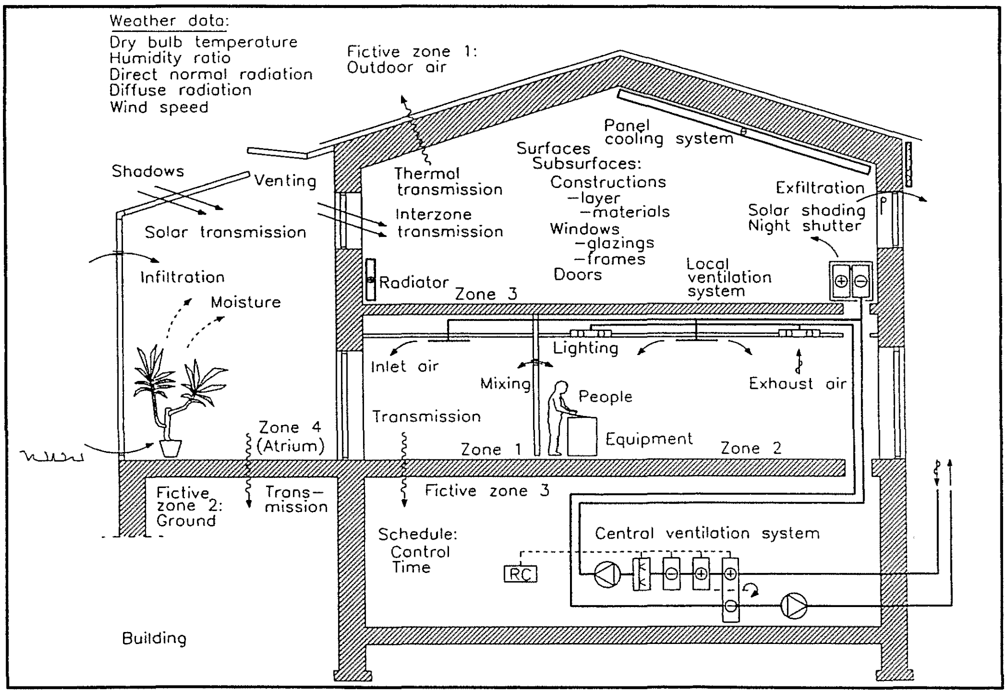


Figure 7.12 Schematic overview of the functions accounted for in the tsbi3 building model [reprinted from Johnsen 1994].

7.3.1 The daylight model in tsbi3

tsbi3 adjusts the amount of artificial lighting needed (only general lighting) according to three different principles: total solar radiation to the zone, daylight illuminance level for a fixed reference point (solar light factors) or by use of externally generated files, e.g. from Superlink. Since interior daylight levels vary continuously according to exterior conditions, tsbi3 approximates the illuminance level for an interior reference point as a relative measure compared to exterior illuminance on a vertical plane (*solar light factor* SF). The solar light factor *SF* at a point on a given surface is defined as the ratio between the illuminance at the point in the room and the total illuminance outside on the surface of the window facade, without shading or shadows from the surroundings. The interior illuminance level (point specific), is a composition of the contribution from direct sun SF1 (inter-reflected component only), diffuse sky light SF2, the reflected light from the ground and the surroundings SF3 or, alternatively, the light transmitted through the solar shading SF4 calculated hour by hour on the basis of solar data in the weather data file used.

For normally used window sizes and room dimensions, curves of the four solar light factors are graphically presented in the tsbi3 User's Guide [Johnsen 1994]. For more special facade design and room geometry, the solar light factors must be estimated either by daylight simulation tools (Superlite and/or Prolight), simplified "hand-calculation" methods (BRS Protractors), or by measurements in an existing building.

Direct sunlight produces a bright spot (variable) in the interior where the reflected light from this spot in the room will act as a source of light. Consequently, only the inter-reflected component from direct sunlight SF1 (see Figure 7.13) is taken into account assuming that most of the direct solar radiation strikes the floor (ρ = 0.1). The variation of SF1 in the room is dependent on sun elevation and azimuth angle, but the calculated curves in tsbi3 assume a solar angle of incidence of 45°. The average value of the inter-reflected contribution to *SF1* is described in [Johnsen 1994, appendix F].

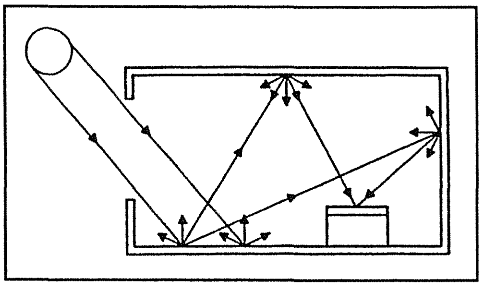


Figure 7.13 The direct component SF1 illustrated only by the inter-reflected component [reprinted from Johnsen 1994].

Light from sky radiation *SF2* (see Figure 7.14) contributes to the illuminance level for an interior reference point due to the visible sky seen through the window. In tsbi3, the sky luminance distribution is assumed to be uniform where the amount of daylight from sky radiation is determined according to algorithms found by [Petersen 1982]. SF2 contains contributions from both the direct and inter-reflected part of the diffuse sky radiation where the algorithms are described in [Johnsen 1994].

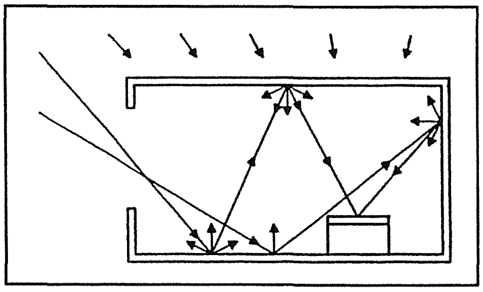


Figure 7.14 The diffuse component SF2 received by the interior from direct and inter-reflected components [reprinted from Johnsen 1994].

The solar light factor *SF3* contains the contribution from the reflected solar light by the ground's surface assuming diffuse ground reflection from the diffuse sky light and the direct sunlight. The reflected component is characterised by the fact that the light must first strike other surfaces in the room, especially the ceiling, before it can reach the interior reference point. SF3 includes only contributions from the inter-reflected part of the light.

For hours where a solar shading is activated, SF1-SF3 are substituted by SF4. The light transmitted through a solar shading is regarded as "diffuse" where *SF4* is used for the solar shading to symbolise the remaining solar light factors for a window with a transmittance of 1 (included in data for window and solar shading). The solar shading coefficient has no influence on the size of SF4 because this has already been taken into account in calculation of the transmitted radiation.

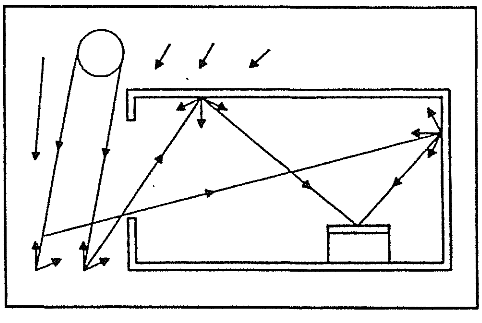


Figure 7.15 The reflected component SF3 received from the ground reflection [reprinted from Johnsen 1994].

7.4 The lighting program Prolight

Prolight is a program for calculation of artificial lighting with a menu-driven interface, developed by Lys & Optik [Prolight 1994], simulating daylight as a light source by a uniform light distribution sphere. The program predicts an interior illuminance distribution on a horizontal and/or a vertical surface for a simple box-shaped room geometry defined by luminaire data, light sources, surface reflectances and a uniform sky luminance distribution. All luminaire data used by Prolight are based on photometric data files using the Nordic LTLI file format with additional physical and luminous dimensions. The output results from Prolight include daylight factors and illuminance values presented as numerical tables or graphically by isolux and 3D-lux distribution curves.

Daylight simulations can be made by using a uniform light distribution and/or a CIE-standard sky distribution for a single window in the facade or ceiling. The interior daylight illuminance level corresponds to the direct component from a uniform sky luminance distribution and the externally reflected component from the ground surface, assuming diffuse ground reflection (10%) modified by a fraction (10%) of the sky luminance otherwise received. The simplified uniform sky luminance distribution does not account for shading from exterior surroundings or the variation of light transmittance dependent on the angle of incidence [Sørensen 1977]. The uniform sky luminance distribution sphere is defined as a Type C Goniometer by the angles of ϕ and γ in a coordiante system recommended by CIE. To simulate the CIE-standard overcast sky, eq. 7.6 was developed to adjust ϕ and γ to the elevation angle, for the previously described sky luminance distribution sphere.

$$\tan(\textit{elevation angle}) = \frac{\sin\phi \cdot \tan\gamma}{\sqrt{1 + (\cos\phi \cdot \tan\gamma)^2}} \qquad 7.6$$

The accuracy of the transformed uniform sky luminance to the CIE-standard overcast sky is shown in Figure 7.16 together with the analytical solution of the uniform sky (eq. 7.3) and the CIE standard overcast sky (eq. 7.4). The results show for the rectangular vertical window, negligible discrepancies in the amount of light from the sky throughout the interior depth [lux] for a rectangular window with the following dimensions: $l \cdot h = 1.5 \cdot 1.5$ m^2, received 0.85 m above floor level.

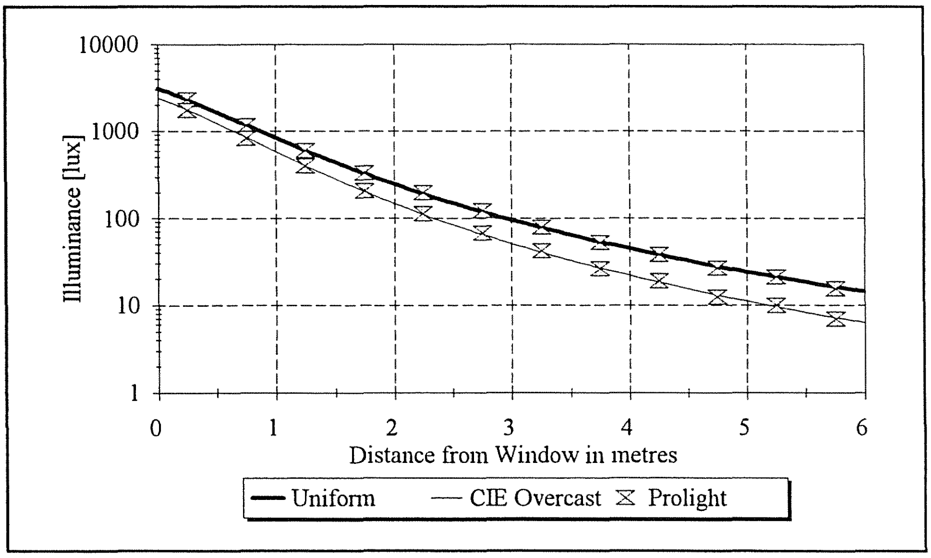


Figure 7.16 Comparison of Prolight's sky component relative to an analytical solution of the sky component for a finite rectangular window.

7.5 Comparison between on-site daylight measurements and simulations

The daylight measurements were conducted in two sparsely furnished, mock-up offices with fixed reflectances of the floor, ceiling and side walls. The offices were orientated 15 degrees west of due south with room dimensions: 3.2 m wide, 6.75 m deep, and 3.1 m high. In the south facade, two windows of equal size with a glazing area of 1.54 m high and 2.16 m wide (window sill height of 1.1

m), with a glass transmission of 80%. The illuminances on the horizontal work plane at 0.85 m above the floor plane, were measured in the symmetry line of the window (see chapter 5). The reflectances of the room surfaces are: left wall – 0.63, right wall – 0.82, front wall (Black) – 0.05, front wall (Grey) – 0.42, rear wall (red bricks) – ≈ 0.40, floor – 0.08, ceiling – 0.89.

For a real, overcast sky condition, the amount of daylight received in the interior depends on the cloud density and type, initial illuminance from the sun and upper sky, transmittance of the clouds, and the inter-reflection between cloud layers and between clouds and the ground [Tregenza 1982]. Compensating for these variations, the ratio between the vertical sky illuminance and global, unobstructed, horizontal illuminance was equal to f_{oc} = 0.396. This is equal to the ratio defined by the CIE - standard overcast sky between vertical and horizontal illuminance.

Figure 7.17 shows the difference between measurements and simulations (Superlite) of the daylight factors with the real, overcast sky and the CIE standard overcast sky model. The simulations, calculated by Superlite, over-estimate the daylight factor at the work plane 0.85 m above floor level throughout the interior. The results show small differences near the window, while relatively larger differences at the back, where the daylight factors are influenced by the inter-reflection algorithm used in Superlite and the inaccurately measured reflectances of the interior surfaces.

The measured and calculated results shown in Table VII.1 support the conclusion that daylight calculations based on the CIE-standard overcast sky and its daylight factors may give incorrect estimates of actual illuminances. The discrepancies arise from several reasons, mainly:

- Variation between the real building and the parameters used in calculation algorithms, i.e. room geometry, inaccuracy of the inter-reflection calculations and the glass transmittance (f.x. angle of incidence, dirt etc.).
- Differences between the real sky luminance distribution and the CIE-standard overcast sky

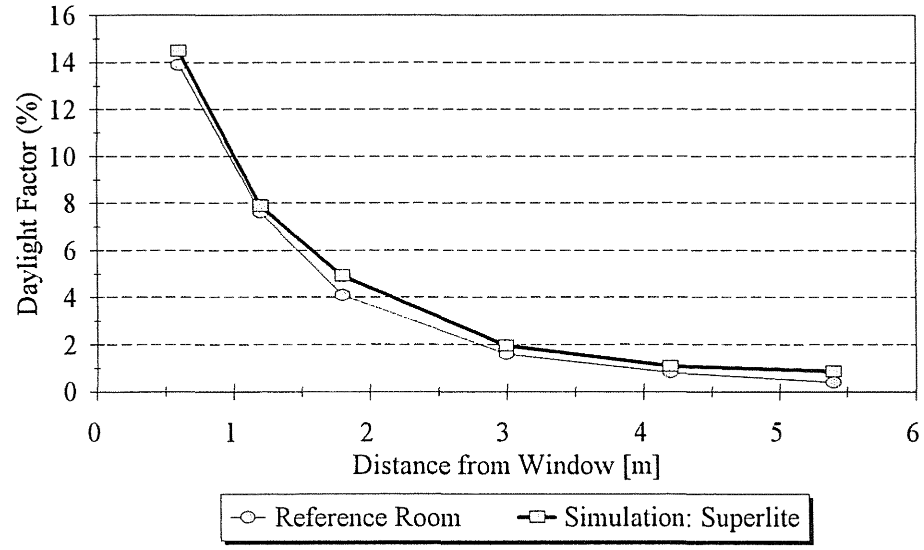


Figure 7.17 Overcast Sky: Measured and calculated daylight factors [%] at the Work Plane for the Daylight Laboratory with traditional window.

Table VII.1 Overcast Sky: The measured and calculated daylight factors in the daylight laboratory.

Work Plane	0.6 m	1.2 m	1.8 m	3.0 m	4.2 m	5.4 m
DF [%] Daylight Laboratory	13.9	7.6	4.1	1.6	0.8	0.4
DF [%] Calculated: Superlite	14.5	7.9	4.9	2.0	1.1	0.9
% Calculated/Measured	+4.2	+3.9	+20.2	+22.5	+35.0	+115.0

8. Energy Analysis of Daylight Utilisation

The Danish Government presented in December 1988, its plan of action on the environment and development, including considerable reductions in the energy demand and more intensive use of natural gas and renewable energy [Danish Ministry of Energy 1990]. These recommendations were based on the report by the World Commission on Environment, the Brundtland Report, and on the United Nations' Environmental Perspective to the year 2000 [Brundtland 1987]. In the report "Energy 2000", the Danish government defined short- and long-term goals of the Danish energy policy. These goals are expressed as increased thermal insulation requirements for new buildings to ensure reduction in heating demands by 25% in 1995 and 50% by the year 2000. The reductions of the energy consumption in the new Danish Building Code include [Aggerholm 1993]:

- Increasing the required insulation standards of new buildings to ensure reduction in heat demand by 25% in 1995 and 50% by the year 2000.
- Utilising technological developments in combination with standards for maximum installed electricity power in fixed lighting installations.

The interest in daylighting systems and control strategies in modern commercial buildings has increased in a time where global environmental issues are of high priority. The contribution to global environmental problems is linked to the emission of CO_2 to the atmosphere from combustion of fossil fuels. The function of a daylighting window is to mediate between the thermal exterior climate all year round and the interior environment, adequate interior natural lighting levels, natural ventilation, view to the exterior, acoustic interchange, etc.

This chapter gives a short and simplified analysis of the possible enhancement of daylight utilisation and the impact on the overall energy balance for a typical office building. The last section shows a comparison between tsbi3 and Superlink (Adeline). The analysis is mainly conducted to show the effect of two different "approaches" to adjust and reduce electric lighting output relative to the calculated interior daylight level.

8.1 The main design data for the office room

In this analysis, several lighting control strategies with tsbi3 have been used to analyse the possibilities and consequences of replacing artificial lighting by daylight when sufficient daylight is available. To take full advantage of the potential energy savings, it is necessary to perform an integrated analysis of natural daylight, artificial light, light control strategies with energy and thermal performance of buildings [Christoffersen 1992a-b]. A module of an office is set up to calculate the impact of combined daylighting and artificial lighting on the thermal balance of a typical office building. The office is a 24-m^2 module and the room's width and depth are 4.0 m by 6.0 m. The room's height is 3.0 m with a window-sill height of 1.0 m. The reflectances of the room surfaces are: walls - 0.4, ceiling - 0.7 and floor - 0.1. The "office model", including a corridor, is orientated towards the four points of the compass. To simulate a realistic office model, the heat transmission loss includes not only the loss through the window wall but also a transmission loss through a "fictive" floor (4 m^2), ceiling (8 m^2) and exterior "gable-wall" (3 m^2). Table VIII.1 shows the general building description used in the analysis.

For this office room, an analysis has been conducted for 3 different glazing types where the window area was varied from 15%, 25% to 40% of the floor area. The base case office module is insulated according to the new Danish Building Regulations 1995 (Danish Ministry of Housing 1995) with a double glazed, lowE coated window (1.6 W/m^2 K). The traditional double glazed window (2.8 W/m^2

K) is only used as standard reference for the Danish Building Regualtions 1982. To accomplish and meet future building regulations, an improved U-value of the vacuum window (0.8 W/m^2 K) with two lowE coatings has been examined.

Table VIII.1 Main design data for the computer program for thermal simulations of buildings, tsbi3 (version B08).

General Building Description	**Office Model:**		
OFFICE, L x W x H	6 x 4 x 3 m		
Weather Data	Danish Test Reference Year (TRY)		
Working Hours	8 am - 5 pm, 5 days a week		
Surfaces - Exterior Wall, U-value W/m^2 K	0.35		
- Interior Wall, U-value W/m^2 K	0.40		
- Exterior Roof and Floor, U-value W/m^2 K	0.20		
- Interior Roof and Floor, U-value W/m^2 K	0.63		
Window	Double glass	Low-E glass	Vacuum glass
Window area (% of the floor area) %	15, 25, 40	15, 25, 40	15, 25, 40
Glazing area (% of the window area) %	70	70	70
Window U-value W/m^2 K	2.8	1.6	0.8
Window Transmission Sun %	76	65	53
Window Transmission Light %	80	77	70
Blinds activated if transmitted radiation exceeds	150 W/m^2	150 W/m^2	150 W/m^2
Shading coefficient including blinds	0.49	0.54	0.55
Indoor temperature - during working hours	21 °C		
- outside working hours, weekends incl.	18 °C		
Infiltration - during working hours	0.50 ac/h		
- outside working hours, weekends incl.	0.25 ac/h		
Mechanical ventilation - during working hours	2.0 ac/h		
- outside working hours, weekends incl.	0.5 ac/h		
Heat recuperation	60%		
Internal load - People, during working hours W/m^2	4.5		
- Equipment, 70% during working hours W/m^2	7.0		
Lighting - Local spots (on during working hours) W/m^2	2.5		
- General lighting (Controlled) W/m^2	10.0		
- Lighting Control	On/off and Dimming		
- Desired Illuminance level on work surface	200 lx		
- Luminous Efficacy on work surface	19.3 lm/W		
Natural ventilation - If indoor temp. exceeds 26°C during working hours	$3\ h^{-1}$		

The internal heat loads from people and equipment are the same for all cases of the analysis. The people load corresponds to two persons occupying the office 75% of the working hours and that the equipment (e.g. PC's and a printer) are used 70% of the time. The control of the indoor temperature has a set point value of 21°C during working hours with a night and weekend set-back of the indoor temperature to 18°C. The warming-up period after night set-back on working days is adjusted by a stepped increase of 1°C from 06.00-09.00. The mechanical ventilation during working hours has a nominal volume flow for the inlet fan corresponding to 2 ac/h with a heat recuperation of 60%. Since offices in Denmark are seldom supplied with mechanical cooling, this has been omitted from the study. Analyses of the indoor air temperature level in the office module in the summer show that the temperature did not exceed 28° C. This indicates no overheating problems since tendencies towards these problems were solved by natural ventilation and the Venetian blinds.

In the winter, solar gains may reduce heating requirements, while in between seasons and in the summer, the utilisation of daylight also increase solar gain and may cause interior overheating problems if not shaded properly. The Venetian blinds are regulated by means of continuous control where the blinds are drawn precisely as much as necessary to keep below the limit for solar radiation (150 W/m^2). One of the drawbacks of Venetian blinds is that they tend to block and frame the exterior view and usually stay down without any adjustments. Simulations show that with the blinds constantly down and a 45° downward tilted slat angle during time of occupancy, this produces an additional heating consumption of approximately 10% compared to the base case with continous blind control. In the base case, the general lighting is switched on all day (light on).

The presented energy analysis is only for the specific office module with the chosen conditions and the results are meant to be used as an indication only and should therefore not be uncritically transferred to any other specific case. The results indicate how the different parameters contribute to the overall building energy balance, including the role of daylighting. In practice, visual comfort and glare play a role in a real setting. Glare problems are not expected to occur often in the simulated situation, as the light coloured, downward tilted Venetian blinds were assumed to be activated when the radiation transmitted through the window exceeded 150 W/m^2.

The first column in Figure 8.1 shows the annual energy balance of the base case with low-E glazing and a 15% window area. The energy consumption for the 4 different orientations is added together. The other two columns show the annual energy consumption with the traditional double glazed window and the vacuum window. The energy balance shows that the internal heat loads from lighting, equipment and people are fairly high during occupancy, since it is assumed that the lighting is switched on all day. Simulations show that the transmission heat loss through the window envelope with the LowE glazing was approximately 50% of the total heat loss (transmission, natural and mechanical ventilation). Changing the U-values to the double glazed window increased the transmission heat loss, so that the heat loss was roughly 65%, while the vacuum window reduced the heat loss to approximately 34%.

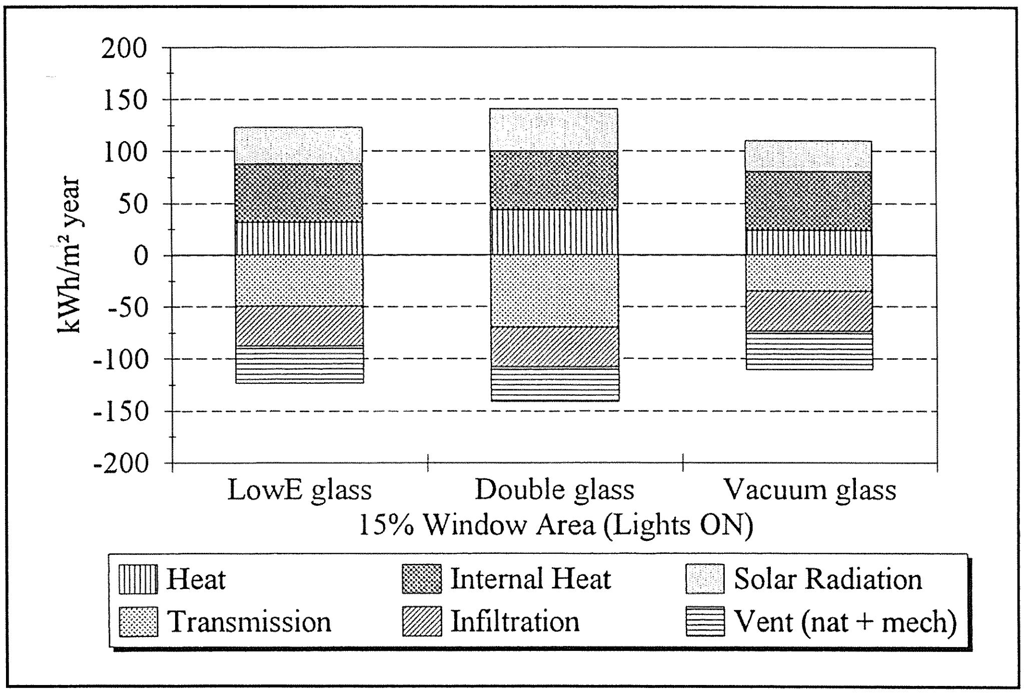


Figure 8.1 Annual Energy Balance - The office module with 15% window area and variable U-value of the window.

8.1.1 The daylight model (tsbi3)

The lighting control model used in tsbi3 adjusts the amount of artificial lighting needed (only general lighting) according to the daylight illuminance level for a fixed reference point. tsbi3 approximates the illuminance level for an interior reference point as a relative measure compared to exterior illuminance on a vertical plane (*solar light factor* SF). The solar light factors used in the analysis are shown in Table VIII.2 for reference points at 3 m and 5.4 m from the window wall: SF1 is for direct sunlight, SF2 for diffuse sky radiation and SF3 for reflected light, while SF4 is used for the diffuse light penetrating a shading device (see chapter 7).

Table VIII.2 Solar light factors used for reference points at 3m and 5.4m from the window facade: SF1 direct sunlight, SF2 diffuse sky radiation, SF3 reflected light, SF4 light from sunshading.

Solar Light Factor		SF 1 [%]	SF 2 [%]	SF 3 [%]	SF 4 [%]
3 m:	15 % Window Area	0.30	4.0	3.5	3.5
	25 % Window Area	0.60	8.2	7.0	6.5
	40 % Window Area	0.82	11.4	9.5	10.0
5.4 m:	15 % Window Area	0.16	1.4	2.0	2.0
	25 % Window Area	0.32	3.0	3.0	2.5
	40 % Window Area	0.42	4.5	4.0	3.5

8.1.2 The lighting control strategies (tsbi3)

There are several forms of controlling the artificial lighting with tsbi3, but the selected control strategies are as follows: on/off, 2-step on/off and continuous dimming.

The principles of *on/off* control systems are, light turned *off* when the interior illuminance from daylight is equal to or above the design illuminance level. The light is turned *on* when the interior daylight level is less than the design illuminance level (Figure 8.2). The multistep on/off control system can supplement the electric lighting output by a power step reduction related to the available amount of natural light (2-4 step on/off). The main problem with the on/off control systems is that they may lead to observable changes in the interior illuminances, which may be distracting for the occupants.

The continuous *dimming* gives a better controlled combination of artificial and natural light, and the control strategy can be almost unnoticeable in use (Figure 8.3). The saving potential using a dimming control system is generally higher than switching control systems, because the interior illuminance generated by electric light is varied in full response to the level of interior daylight.

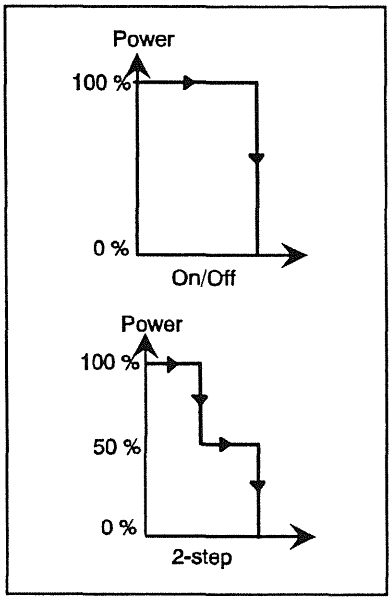


Figure 8.2 Illustration of an on/off lighting control strategy.

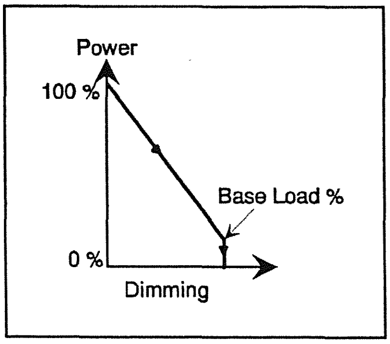


Figure 8.3 Illustration of a dimming lighting control strategy.

In tsbi3, the lighting system is divided into general lighting (ceiling) and task lighting. The control is different for the two types of lighting, as the work place illumination is assumed always to be switched on during working hours, whilst the general lighting is controlled according to the needs. During each hour of the time definition, the daylight illuminance level at the reference point is calculated and lighting switched on if necessary in order to achieve the desired lighting level. The defined lighting power is converted to heat, where the converted heat is given to the indoor air and the zone's surfaces. Two types of light sources can be selected, either *incandescent* or *fluorescent* lighting. The type is of significance regarding lighting *control* as the power consumed is not proportional with the light emitted (Figure 8.4). For an incandescent source, the ratio between power and lumen output is calculated according to eq. 8.1 [Johnsen 1994]:

$$P = 0.01 \cdot (-0.00532 \cdot f^2 + 1.25296 \cdot f + 27.56) \cdot \mathit{genlight} \quad [\mathrm{kW}] \qquad 8.1$$

and for the fluorescent type according to eq. 8.2:

$$\begin{aligned} P &= (0.9f + 0.1) \cdot \mathit{genlight} && \mathit{for} \quad f > 0.1 \\ P &= 0.0 && \mathit{for} \quad f \leq 0.1 \end{aligned} \qquad 8.2$$

where P is the power needed to achieve the desired lighting level, kW
f is the desired lighting level in percentage of the nominal level, %
genlight is the nominal lighting level, lux

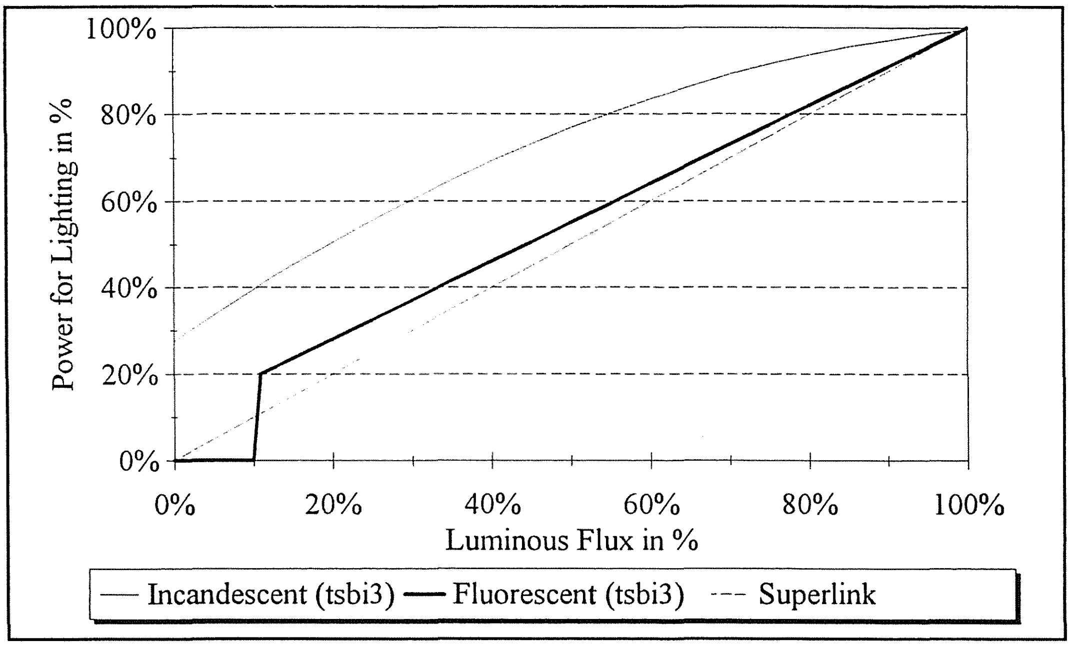


Figure 8.4 Lighting control of the incandescent or fluorescent light sources in tsbi3 and Superlink - the power consumed (tsbi3) is not proportional with the light emitted.

8.2 Energy analysis of combined thermal and visual comfort

To accomplish the perspectives in the Danish energy plan, an intelligent use of natural light in office buildings will provide a potential factor for decreasing energy produced from fossil fuels. In modern commercial buildings, light is provided mostly by daylight and partly by electric lighting. In buildings which are not supported by an electric lighting control system, the lights tend to stay on and are seldom switched off again when daylight alone is sufficient. To take full advantage of the potential energy savings, it is essential to provide the building with control systems that adjust and reduce the electric light output according to the available daylight.

8.2.1 Energy analysis: 15% window area

Table VIII.3 shows the consumed energy in kWh/m^2·y for lighting, heating, and heating plus lighting, a "cost index" for heating and lighting, and the percentage increase or decrease relative to the base case (15% window area with lowE glazing) for the considered daylight strategies. The percentage savings are shown in relation to the base case assuming that the artificial lighting switched on all day. The energy consumption for the different orientations is added together. The values in Table VIII.3 show heating (H) (column 3), lighting (L) (column 5), and the sum of the two sources heating+lighting (H+L) (column 7) and a "cost index" (H+2*L) (column 9) based on the use of natural gas for heating (current Danish energy rates). The general lighting is adjusted according to the daylight illuminance level on the work plane for reference points at 3 and 5.4 m from the window wall. The desired illumination level in the selected reference point is 200 lux. Table VIII.3 shows for a 15% window area with lowE glazing the energy consumption of heating and lighting, where the 4 different orientations are added together.

The simulations show that by use of daylight as work surface illuminance, between 27% and 62% of general lighting (L) energy might be saved. Controlling the general lighting by the on/off and dimming control strategies according to the reference point in the middle of the room (3 m), show that the savings potential is 50% and 62%, respectively. Even though the daylight level at the back (5.4 m) is lower, daylight is almost equally received from the direct and the inter-reflected component, providing a saving of 27-46% of the lighting consumption. The reduced lighting consumption, by selecting the reference point at the back of the room shows the importance of lighting control strategy and position of sensor, since a significant part of the lighting energy savings may easily be lost. The increased lighting consumption with the on/off strategy at 5.4 m compared to the reference point at 3 m is merely a result of the strategy itself and the reduced daylighting level, since no intermediate steps exist between having all fixtures *on* and having them all *off*. The reduction in lighting energy savings with the on/off control (at 5.4 m) compared to the 2-step on/off and the dimming control strategy is 12% and 26%, respectively.

Table VIII.3 Window Area 15% (LowE): Heating and lighting consumption for different lighting control strategies (savings -, additional consumption +) for a reference point at 3 m and 5.4 m.

Office Model - 15% window area	Strategy	Heating (H) kWh/m^2·y	%	Lighting (L) kWh/m^2·y	%	H + L kWh/m^2·y	%	**Cost index** H + 2*L kWh/m^2·y	%
Base Case - LowE	on	31,4	0	29,4	0	60,8	0	90,2	0
On/Off (3 m)	on/off	35,4	13	14,7	-50	50,1	-18	64,8	-28
2-step On/Off (3 m)	2-on/off	36,7	17	13,1	-55	49,8	-18	62,9	-30
Dimming (3 m)	dimming	38,2	22	11,3	-62	49,5	-19	60,8	-33
On/Off (5.4 m)	on/off	32,2	3	21,6	-27	53,8	-12	75,4	-16
2-step On/Off (5.4 m)	2-on/off	33,2	6	19,1	-35	52,3	-14	71,4	-21
Dimming (5.4 m)	dimming	35,1	12	15,9	-46	51,0	-16	66,9	-26

While lighting control will reduce the energy for electrical lighting, it will always increase energy consumption for heating because of the reduced internal loads from the lighting system. When the increase in heating energy consumption is taken into account, the total energy savings are reduced to 12-19%. Implementing the "cost index" (H+2*L) (current Danish energy rates), based on the use of natural gas for heating, the energy cost savings show that the saving potential is 16-33%.

The developments in window and glass technology have improved the U-value of the window, so that a well-insulated window drastically decreases the heat loss through the envelope. Table VIII.4 shows the energy consequences (kWh/m^2·y) of improving the U-value of the window (vacuum window) for the office module with 15% window area. The traditional double glazed window is used as a standard requirement in the Danish Building Regulations 1982. The heating and lighting consumptions, where the 4 orientations are added together, are compared to the base case (LowE) assuming that the lighting is switched *on* during occupancy. The general lighting is controlled by the reference point in the middle of the room (3 m) with a daylight illuminance set-point of 200 lux.

Table VIII.4 Window Area 15% (Variable glazing): Heating and lighting consumption for different lighting control strategies (savings -, additional consumption +) for a reference point at 3 m.

Office Model (3 m) - 15% window area	Strategy	Heating (H) kWh/m^2·y	%	Lighting (L) kWh/m^2·y	%	H + L kWh/m^2·y	%	**Cost index** H + 2*L kWh/m^2·y	%
Base Case - LowE	on	31,4	0	29,4	0	60,8	0	90,2	0
Double glazing	on	43,3	38	29,4	0	72,7	20	102,1	13
On/Off	on/off	48,3	54	14,4	-51	62,7	3	77,1	-15
Dimming	dimming	51,2	63	11,2	-62	62,4	3	73,6	-18
Vacuum glazing	on	24,2	-23	29,4	0	53,6	-12	83,0	-8
On/Off	on/off	27,3	-13	15,3	-48	42,6	-30	57,9	-36
Dimming	dimming	30,2	-4	11,7	-60	41,9	-31	53,6	-41

Because the double glazed window increases the solar transmission coefficient from 65% to 76%, the solar gain is increased by roughly 16%. Still, the calculations show an increase of the heating consumption by approximately 38% compared to the base case. The vacuum window with a solar transmission coefficient of 53% reduces the solar gain by approximately 16%. However, the simulations with the vacuum window and the light on during occupancy show that the heating consumption is reduced by approximately 23%. Applying the on/off and dimming control strategies to the office module with the vacuum window, shows that the saved heating consumption is reduced to 13% and 4%, respectively.

Table VIII.4 also shows the influence on the energy balance for two different control strategies (on/off and dimming) compared to the light switched *on*. With on/off control, the savings potential for electric lighting is between 48% and 51%, and with dimming control, the savings potential is between 60% and 62% for the vacuum and double glazed window, respectively. The slightly higher general lighting consumption with the vacuum window is the consequence of the reduced light transmission from 80% to 70%. Combining the heating and lighting consumption for the vacuum window (H+L), the total energy savings with the lighting control strategies are reduced to 30-31%, while the energy cost savings are slightly higher. The double glazed window shows only a savings potential of 15-18% compared to the LowE with lights on, when using the "cost index".

8.2.2 Energy analysis: Variable window area

The results in Table VIII.3 and Table VIII.4 show the possible energy savings for the 15% window area with different glazings and U-values. In practice the improvement of the window U-values also leads to a reduction of the transmitted natural light. It is therefore necessary either to enlarge the window area or increase the amount of artificial lighting in order to obtain the same interior illuminance level. However, fulfilment of some of the visual comfort criteria described in chapter 4 by increasing the window area may result in increased energy consumption and side effects like thermal discomfort, glare problems etc. Different studies have suggested that the preferred and minimum acceptable window size will occupy at least 25-30% of the window wall area [Ne'eman 1970, Keighly 1973 a-b, Ludlow 1976]. An analysis of increased window area for the lowE and vacuum window is described in Table VIII.5 and Table VIII.6. The base case is still the 15% window area with lowE glazing and the lights on during occupancy, where the window corresponds to a window-to-wall area of 30%. Table VIII.5 shows the energy consumption of heating and lighting for different window areas (window-to-floor area ratios of 15, 25 and 40%) with lowE glazing, where the 4 different orientations are added together.

The greater window area in Table VIII.5 increases the transmission heat losses and the heating consumption, but it will also increase the daylight illuminance level. An analysis shows that for the 25% and 40% window areas with the LowE glazing, approximately 67% and 82% of the total heat loss (transmission, infiltration, natural and mechanical ventilation), respectively, is heat loss through the windows. The increased window area with the lights on during occupancy causes an additional heating consumption of 13% (LowE 25%) and 36% (LowE 40%). With on/off and dimming control strategies, the lighting savings potential is 63% and 69% (LowE 25%) and 66% and 71% (LowE 40%). Whilst lighting control reduces the electrical lighting energy, it increases energy consumption for heating. When the increase in heating energy consumption is taken into account, the total energy savings are reduced to 12-13% (LowE 25%) and 2% (LowE 40%). The reduced savings potential with increased window areas indicates that an "optimum" window size may be found, but it also shows that it is essential to provide the building with control systems that adjust and reduce unneccessary use of electric lighting. The table also shows that implementing the "cost index" (H+2*L) increases the savings potential to 23-30%, which emphasises that use of a "cost index" (or environment index) may have great influence on the optimum window size.

Table VIII.5 Variable Window Area (LowE): Heating and lighting consumption for different lighting control strategies (savings -, additional consumption +) for a reference point at 3 m.

Office Model (LowE) - Variable Window Area	Strategy	Heating (H)		Lighting (L)		H + L		**Cost index H + 2*L**	
		kWh/m^2·y	%	kWh/m^2·y	%	kWh/m^2·y	%	kWh/m^2·y	%
Base Case - LowE (15%)	on	31,4	0	29,4	0	60,8	0	90,2	0
Base Case - LowE (25%)	on	35,5	13	29,4	0	64,9	7	94,3	5
On/Off	on/off	42,0	34	11,0	-63	53,0	-13	64,0	-29
Dimming	dimming	44,3	41	9,2	-69	53,5	-12	62,7	-30
Base Case - LowE (40%)	on	42,8	36	29,4	0	72,2	19	101,6	13
On/Off	on/off	49,6	58	10,1	-66	59,7	-2	69,8	-23
Dimming	dimming	51,2	63	8,5	-71	59,7	-2	68,2	-24

Figure 8.5 shows the total energy balance for the three different window areas with lowE glazing. The internal heat loads from lighting (variable due to on/off lighting control strategy) and the amount of equipment and people are fairly high during occupancy, but the energy balances show that heating (radiators and mechanical ventilation) is the largest contributor to the energy balance for window areas of 25% and 40%.

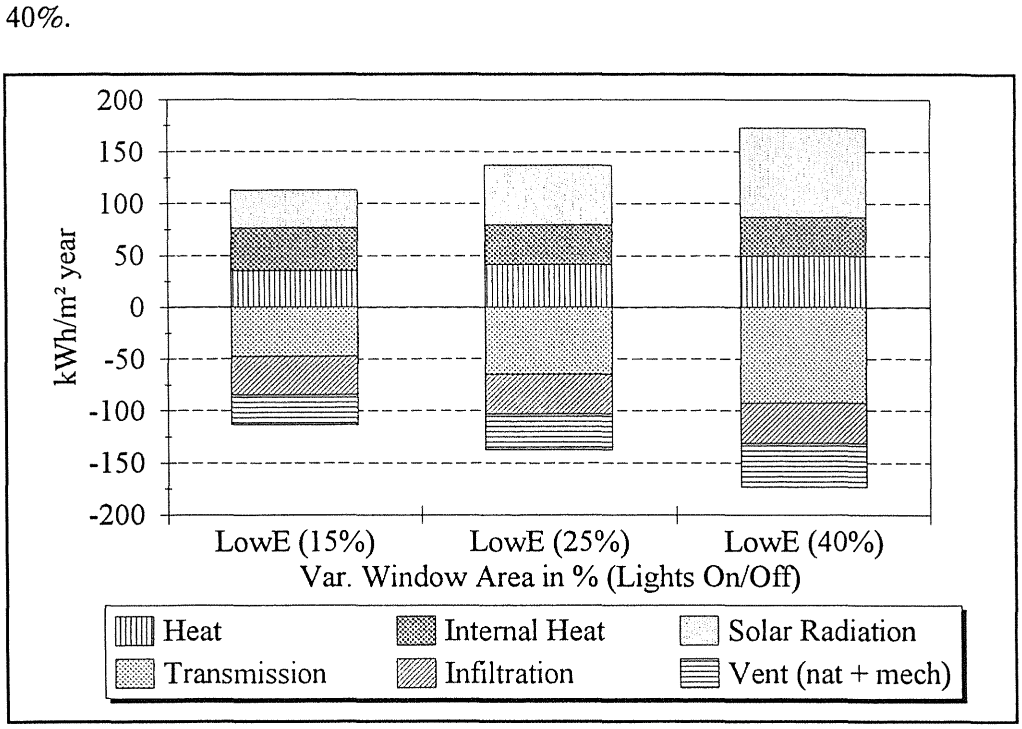


Figure 8.5 Annual Energy Balance (LowE) - The office module with variable window area and on/off lighting control strategies for a reference point at 3 m.

Table VIII.6 shows the energy consumption of heating and lighting for different window areas (15%, 25% and 40%) with the vacuum window, where the 4 different orientations are added together. The improved U-value of the window reduces the transmission heat loss through the window by 50% (Vacuum 25%) and 69% (Vacuum 40%) of the total heat loss.

Table VIII.6 Variable Window Area (Vacuum): Heating and lighting consumption for different lighting control strategies (savings -, additional consumption +) for a reference point at 3 m.

Office Model - Variable Window Area	Strategy	Heating (H)		Lighting (L)		H + L		Cost index H + 2*L	
		kWh/m^2·y	%	kWh/m^2·y	%	kWh/m^2·y	%	kWh/m^2·y	%
Base Case - LowE (15%)	on	31,4	0	29,4	0	60,8	0	90,2	0
Vacuum - (25%)	on	23,5	-25	29,4	0	52,9	-13	82,3	-9
On/Off	on/off	29,1	-7	11,4	-61	40,5	-33	51,9	-42
Dimming	dimming	31,0	-1	9,4	-68	40,4	-34	49,8	-45
Vacuum - (40%)	on	23,4	-25	29,4	0	52,8	-13	82,2	-9
On/Off	on/off	26,8	-15	10,2	-65	37,0	-39	47,2	-48
Dimming	dimming	30,7	-2	8,7	-70	39,4	-35	48,1	-47

The control strategies applied, on/off and dimming, show that the lighting energy consumption is reduced by 61% to 70%. The results show that, in spite of the reduction in the heat gains from lighting and increased window area, a reduction in energy for heating of 1-15% can be achieved by improving the window envelope. Increasing the window area from 25% to 40% with the lights on during occupancy causes no increase in the heating consumption (25%) compared to the lowE window (15% window area). When the heating energy consumption is taken into account, the total energy savings are 33-39%, while the energy costs show an increased saving potential of 42-48%. A total reduction of 50% of the needs for energy produced from fossil fuels, as described in the Brundtland Report, "Our Common Future," and in the Danish energy plan, Energy 2000, can therefore be regarded as an ambitious but not unrealistic goal.

Figure 8.6 shows the total energy balance for the 15% window area with lowE glazing and the vacuum glazing for three different window areas. The internal heat loads from lighting (variable due to on/off lighting control strategy) and the amount of equipment and people are fairly high during occupancy, so the energy balances show that the internal heat loads are the largest contributor to the energy balance. The heating consumption (radiators and mechanical ventilation) with vacuum windows (15-40%) is less than the lowE window (15% window area).

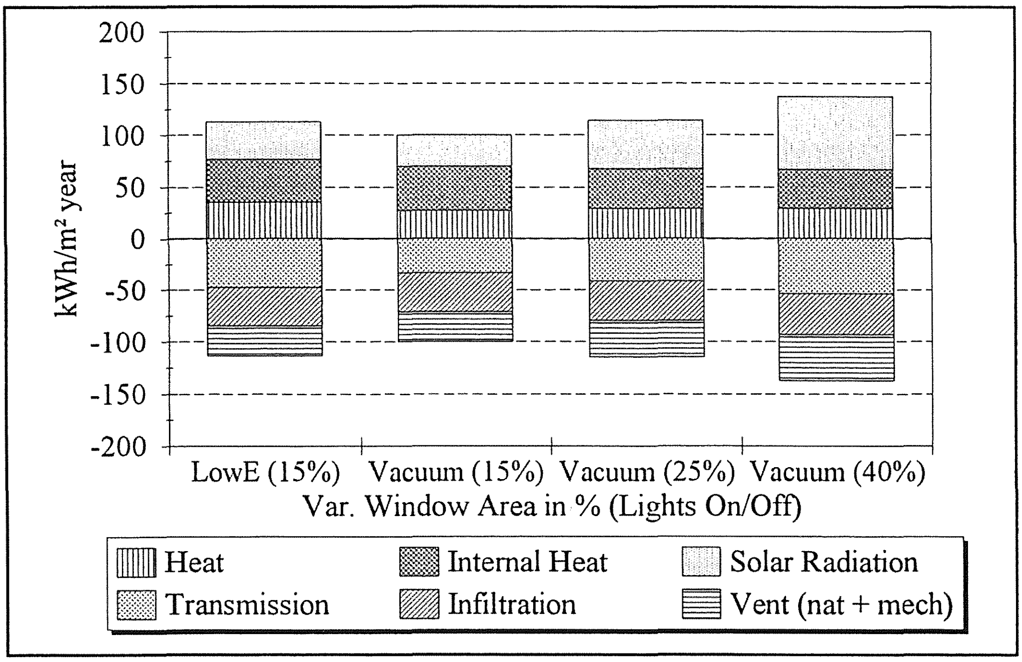


Figure 8.6 Annual Energy Balance (LowE 15% and Vacuum 15-40%) - The office module with variable window area and on/off lighting control strategies for a reference point at 3 m.

8.2.3 Energy analysis: LowE glazing with variable window area and orientations

Table VIII.7 to Table VIII.9 show the consumed energy in kWh/m^2·y for lighting, heating, and heating plus lighting, a "cost index" for heating and lighting, and the percentage increase or decrease relative to the 15% window area with lowE glazing for the considered daylighting strategies. The lighting control strategies are on/off and continuous dimming with a reference point at 3 m from the window wall. In Table VIII.8, the resulting energy consumptions are the mean values of the east and west facing office. It should be kept in mind that the energy analyses are valid for the specific office module and the conditions described in Table VIII.1 and the results should therefore not be uncritically transferred to general contexts.

Increasing the window area will increase the transmission heat loss through the window envelope and the heating consumption. For the 15%, 25% and 40% window area, approximately 51%, 67% and 82% of the total heat losses (transmission, infiltration, natural and mechanical ventilation), respectively, are heat losses through the windows.

North

Table VIII.7 shows the heating and lighting consumption for the north-orientated office module. The simulations reveal that the largest energy savings are presented by the 15% window, while increasing the window area to 25% causes a slightly reduced savings potential. If the U-value of the window is not improved, the 40% window area facing North is not suitable for climates like in Denmark. The on/off and dimming control strategies show that the lighting consumption can be reduced by 48-71%, highest with the continuous dimming and 40% window area. Accounting for the increased heating consumption, the results show for the 15% and 25% window area that the total energy savings are 8-

16%, while the 40% window causes an additional energy consumption of 6%. The energy cost savings with the 15% and 25% window were increased to 27-30%. The 40% window only shows a savings potential (16-18%) when implementing the "cost index".

Table VIII.7 North - Variable Window Area: Heating and lighting consumption for different lighting control strategies (savings -, additional consumption +) for a reference point at 3 m.

Office Model: N - Variable Window Area	Strategy	Heating (H) kWh/m^2·y	%	Lighting (L) kWh/m^2·y	%	H + L kWh/m^2·y	%	**Cost index** H + 2*L kWh/m^2·y	%
Base Case - LowE (15%)	on	35,3	0	29,4	0	64,7	0	94,1	0
On/Off	on/off	39,5	12	15,3	-48	54,8	-15	70,1	-26
Dimming	dimming	42,7	21	11,6	-61	54,3	-16	65,9	-30
Base Case - LowE (25%)	on	41,1	16	29,4	0	70,5	9	99,9	6
On/Off	on/off	48,4	37	11,3	-62	59,7	-8	71,0	-25
Dimming	dimming	50,4	43	9,3	-68	59,7	-8	69,0	-27
Base Case - LowE (40%)	on	50,7	44	29,4	0	80,1	24	109,5	16
On/Off	on/off	58,7	66	10,2	-65	68,9	6	79,1	-16
Dimming	dimming	60,4	71	8,5	-71	68,9	6	77,4	-18

East/West

Table VIII.8 shows the heating and lighting consumption for the east/west-orientated office module. The energy analysis shows that increasing the window area from 15% to 25% with lowE glazing can be applied to building constructions without significant increase in their energy consumption. The reduction of the lighting consumption shows insignificant differences compared to the North office. The general lighting with the applied control strategies was reduced to 50-71%. Combining the heating and lighting consumption, the results show that the total energy savings were 12-18% for the 15% and 25% window areas, while the 40% window area caused no additional energy consumption compared to base case. The energy cost savings with the 15% and 25% window were increased to 28-32%, while the 40% window showed that the saving potential is less (21-23%).

Table VIII.8 East/West - Variable Window Area: Heating and lighting consumption for different lighting control strategies (savings -, additional consumption +) for a reference point at 3 m.

Office Model: E/W - Variable Window Area	Strategy	Heating (H) kWh/m^2·y	%	Lighting (L) kWh/m^2·y	%	H + L kWh/m^2·y	%	**Cost index** H + 2*L kWh/m^2·y	%
Base Case - LowE (15%)	on	32,4	0	29,4	0	61,8	0	91,2	0
On/Off	on/off	36,3	12	14,8	-50	51,1	-17	65,9	-28
Dimming	dimming	39,2	21	11,3	-62	50,5	-18	61,8	-32
Base Case - LowE (25%)	on	37,0	14	29,4	0	66,4	7	95,8	5
On/Off	on/off	43,6	35	11,0	-63	54,6	-12	65,6	-28
Dimming	dimming	45,5	40	9,1	-69	54,6	-12	63,7	-30
Base Case - LowE (40%)	on	45,0	39	29,4	0	74,4	20	103,8	14
On/Off	on/off	52,0	60	10,1	-66	62,1	0	72,2	-21
Dimming	dimming	53,5	65	8,5	-71	62,0	0	70,5	-23

South

Table VIII.9 shows the heating and lighting consumption for the south-orientated office module. Contrary to the other 3 orientations, the energy analysis shows that the 40% window area with the lowE glazing can be used in the window envelope even in climates like in Denmark. The general lighting with the applied control strategies was reduced to 53-71%. Combining the heating and lighting consumption, the results show that the total energy savings were 16-22%, while the energy cost savings were increased to 32-38%.

Table VIII.9 South - Variable Window Area: Heating and lighting consumption for different lighting control strategies (savings -, additional consumption +) for a reference point at 3 m.

Office Model: S - Variable Window Area	Strategy	Heating (H)		Lighting (L)		H + L		Cost index H + 2*L	
		$kWh/m^2 \cdot y$	%	$kWh/m^2 \cdot y$	%	$kWh/m^2 \cdot y$	%	$kWh/m^2 \cdot y$	%
Base Case - LowE (15%)	on	25,4	0	29,4	0	54,8	0	84,2	0
On/Off	on/off	29,5	16	13,8	-53	43,3	-21	57,1	-32
Dimming	dimming	31,8	25	10,8	-63	42,6	-22	53,4	-37
Base Case - LowE (25%)	on	26,7	5	29,4	0	56,1	2	85,5	2
On/Off	on/off	32,3	27	10,7	-64	43,0	-22	53,7	-36
Dimming	dimming	33,9	33	9,0	-69	42,9	-22	51,9	-38
Base Case - LowE (40%)	on	30,4	20	29,4	0	59,8	9	89,2	6
On/Off	on/off	35,9	41	9,9	-66	45,8	-16	55,7	-34
Dimming	dimming	37,3	47	8,4	-71	45,7	-17	54,1	-36

8.3 Comparison of tsbi3 and Superlink

The comparison between tsbi3 and Superlink was mainly conducted to show the effect of two different "approaches" to adjust and reduce electric lighting output relative to the calculated interior daylight level. The comparison also examines the "accuracy" of the solar light factors used in tsbi3. The simulations showed that by use of normal window sizes and room dimensions, the curves in the tsbi3 User's Manual will often be sufficient to perform a fast and "accurate" integrated analysis of the use of natural light and artificial light, and the impact of light control strategies on energy and the thermal performance of a building. The Superlink program is more time-consuming, but there are more options available, especially the use of several reference points simultanously to control the artificial lighting.

Superlink uses an average sky model developed by [Aydinly 1981] to model the full range of actual sky conditions for several sun positions on the 15th of each month and for each hour of the day [Adeline 1994 f-g]. The interior work plane illuminance level is simulated for three CIE-standard sky conditions; overcast sky, clear sky without sun, and clear sky with sun. Depending on the amount of daylighting available, the supplemented artificial lighting corresponds to the maximum lighting power or a fraction of it, depending on the applied lighting control strategy. The results of the hourly demands for artificial lighting over the whole year are used as input to tsbi3.

8.3.1 Comparison of 15% window area

The results presented are for the specific office module shown in Table VIII.1. The simulations have been carried out for a low-E glazing, orientated towards the four points of the compass with a window area of 15% of the floor area. There are no concerns regarding the indoor thermal conditions (e.g. risk of overheating), since the results are only meant to indicate how daylight contributes to the heating and lighting consumptions. Furthermore, the supplied heating power maintained a fixed interior temperature of 21°C throughout the year and the solar shading was not activated during the simulations. The remaining conditions are as shown in Table VIII.1.

Table VIII.10 shows the consumed energy in $kWh/m^2 \cdot y$ for lighting, heating, and heating plus lighting, a "cost index" for heating and lighting, and the percentage increase or decrease relative to the base case (15% window area) for the considered daylight strategies. The percentage savings are shown in relation to the base case assuming the lighting is switched on all day. The two lighting control strategies simulated are the 2-step on/off and the continuous dimming.

Table VIII.10 Window Area 15% (LowE): Heating and lighting consumption for different lighting control strategies (savings -, additional consumption +) for a reference point at 3 m.

Office Model (LowE) - 15% window area	Strategy	Heating (H) kWh/m²·y	%	Lighting (L) kWh/m²·y	%	H + L kWh/m²·y	%	**Cost index** H + 2*L kWh/m²·y	%
Base Case	on	46,6	0	29,4	0	76,0	0	105,4	0
2-On/Off: tsbi3	2-on/off	52,5	13	13,1	-55	65,6	-14	78,7	-25
2-On/Off: Superlink	2-on/off	52,3	12	13,4	-54	65,7	-14	79,1	-25
Dimming: tsbi3	dimming	54,0	16	11,3	-62	65,3	-14	76,6	-27
Dimming: Superlink	dimming	52,8	13	13,0	-56	65,8	-13	78,8	-25

The results show that if daylighting is properly utilised as work surface illuminance, between 54% and 62% of lighting (L) energy may be saved. The 2-step on/off strategy switches the lights *on* at full power when the interior daylight level is less than 50% of the desired work plane illuminance level and *off* when the daylight level is equal to or above the required illuminance level. The dimming control system varies the artificial illuminance level in a "precise" reply to the incident level of daylight, which increases the savings potential of the lighting energy consumption. However, some of the saved lighting energy results in an increased energy consumption for heating. The reduced internal heat from the artificial lighting due to the on/off and dimming control strategy increases the heating consumption by 12 and 16%, respectively. Combining the heating and lighting consumption (H+L) showed that the total energy savings are reduced to 13-14%. Implementing the "cost index" (H+2*L), based on the use of natural gas for heating, the energy cost savings showed that the savings potential is 25-27%.

The main differences between the two methods are difficult to describe, since the algorithms used in Superlink are not fully documented. However, one difference is that the electric lighting in Superlink is assumed to be proportional to the light emitted while this is not the case for tsbi3. The 2-step on/off control strategy is "less" affected by the difference in the ratio between power and lumen output, since this discrepancy mainly affects low lighting levels. Another difference is that Superlink uses the average sky model simulated by three CIE-standard sky conditions for several sun positions, the 15th of each month and each hour of the day. With these values, Superlink estimates the interior daylight work surface illuminance level by a sunny interval (SSP) and an interval without sun (1-SSP). SSP is the hourly sunshine probability, which is defined as the ratio of sunshine during one hour compared to the maximum possible amount of sunlight that could occur. In tsbi3, the interior illuminance level is calculated by the contribution from direct sun SF1 (inter-reflected component only), diffuse sky light SF2 and the reflected light SF3. The interior daylight illuminance level is calculated hour by hour on the basis of the solar data in the Danish weather data file.

8.3.2 Comparison of 15% window area with different orientations

The energy consumption of heating and lighting for the different orientations is shown in Table VIII.11 to Table VIII.13. The lighting control strategies are the 2-step on/off and the continuous dimming with a reference point at 3 m from the window wall. In Table VIII.12, the resulting energy consumptions for the east/west facing office are the mean values.

North

Table VIII.11 shows the heating and lighting consumption for the north-orientated office module. The additional heating consumption with the 2-step on/off and dimming control strategies is 13% and 16%, while the lighting energy savings are 53% and 61%, respectively. tsbi3 estimates higher interior daylight levels due to the uniform sky luminance distribution which again will result in a reduced need for artificial lighting compared to Superlink (CIE overcast sky). The 2-step on/off control strategy shows only a small difference in the lighting energy used. The results also show that the dimming control strategy used in Superlink predicts higher lighting consumption (13.2 kWh/m²·y) than tsbi3 (11.6 kWh/m²·y). Superlink varies the lighting power output within a 0-100% range (Figure 8.4) whereas tsbi3 regulates within a 10-100% range and below this range causes the lights to be turned off. Combining heating and lighting consumption shows no difference in the total energy savings (11%).

Table VIII.11 North - Window Area 15% (LowE): Heating and lighting consumption for different lighting control strategies (savings -, additional consumption +) for a reference point at 3 m.

Office Model: N - 15% window area	Strategy	Heating (H)		Lighting (L)		H + L		Cost index H + 2*L	
		kWh/m^2·y	%	kWh/m^2·y	%	kWh/m^2·y	%	kWh/m^2·y	%
Base Case	on	52,6	0	29,4	0	82,0	0	111,4	0
2-On/Off: tsbi3	2-on/off	59,4	13	13,6	-54	73,0	-11	86,6	-22
2-On/Off: Superlink	2-on/off	59,4	13	13,8	-53	73,2	-11	87,0	-22
Dimming: tsbi3	dimming	61,2	16	11,6	-61	72,8	-11	84,4	-24
Dimming: Superlink	dimming	60,1	14	13,2	-55	73,3	-11	86,5	-22

East/West

Table VIII.12 shows the heating and lighting consumption for the east/west-orientated office module. It shows that the additional heating consumption with the 2-step on/off and dimming control strategies was 11% to 15%, while the lighting energy savings were 53% and 62%, respectively. The main difference between tsbi3 and Superlink is that tsbi3 assumes that the direct sun component has a fixed angle of incidence of 45° (SF1).

Table VIII.12 East/West - Window Area 15%: Energy consumption of heating and lighting for different lighting control strategies (savings -, additional consumption +) for a reference point at 3 m.

Office Model: E/W - 15% window area	Strategy	Heating (H)		Lighting (L)		H + L		Cost indexs H + 2*L	
		kWh/m^2·y	%	kWh/m^2·y	%	kWh/m^2·y	%	kWh/m^2·y	%
Base Case	on	48,1	0	29,4	0	77,5	0	106,9	0
2-On/Off: tsbi3	2-on/off	53,6	11	13,2	-55	66,8	-14	80,0	-25
2-On/Off: Superlink	2-on/off	53,2	11	13,7	-53	66,9	-14	80,6	-25
Dimming: tsbi3	dimming	55,2	15	11,3	-62	66,5	-14	77,8	-27
Dimming: Superlink	dimming	53,9	12	13,2	-55	67,1	-13	80,3	-25

South

Table VIII.13 shows the heating and lighting consumption for the south-orientated office module. The additional heating consumption with the 2-step on/off and dimming control strategies was 14% to 18%, while the lighting energy savings were 55% and 63%, respectively. The dimming control strategy used in Superlink predicts higher lighting consumption (13.1 kWh/m^2·y) than the 2-step on/off switching (12.4 kWh/m^2·y). The results with Superlink for the south-orientated office show an inconsistent savings potential by use of the dimming control system, since the lighting consumption was expected to be lower than that with on/off switching control strategy.

Table VIII.13 South - Window Area 15%: Energy consumption of heating and lighting for different lighting control strategies (savings -, additional consumption +) for a reference point at 3 m.

Office Model: S - 15% window area	Strategy	Heating (H)		Lighting (L)		H + L		Cost indexs H + 2*L	
		kWh/m^2·y	%	kWh/m^2·y	%	kWh/m^2·y	%	kWh/m^2·y	%
Base Case	on	37,8	0	29,4	0	67,2	0	96,6	0
2-On/Off: tsbi3	2-on/off	43,3	15	12,4	-58	55,7	-17	68,1	-30
2-On/Off: Superlink	2-on/off	43,5	15	12,4	-58	55,9	-17	68,3	-29
Dimming: tsbi3	dimming	44,5	18	10,8	-63	55,3	-18	66,1	-32
Dimming: Superlink	dimming	43,2	14	13,1	-55	56,3	-16	69,4	-28

Sammenfatning og konklusioner

SBI-rapport 258: Dagslysudnyttelse i kontorbygninger

Dagslys har i de seneste 10 år fået fornyet opmærksomhed på grund af de æstetiske muligheder for, samt evnen til, at opfylde menneskets biologiske og globale økologiske behov. Dagslys transmitteres gennem vinduer ind i bygninger og giver variation i lysintensitet, lysfarve og lysretning med skiftende karakter fra solopgang til solnedgang, fra dag til dag og fra årstid til årstid. Sollyset forbindes også med høje belysningsstyrker og fordelen af passiv solvarme, men samtidig med uundgåelige bieffekter så som risiko for overophedning, blænding etc.

Almindelige vinduer i bygningers facader giver en skæv luminansfordeling i rummet, idet området tæt ved vinduet kan være meget lyst, mens den bagerste del af rummet ofte opfattes som værende mørkt. Nye (innovative) dagslyssystemer kan reducere denne forskel og samtidig udvide muligheden for at udnytte dagslyset uden at forringe de visuelle kvaliteter eller den termiske komfort. Formålet med undersøgelsen har været at evaluere forskellige dagslyssystemers kvalitative og kvantitative virkninger herunder at undersøge systemernes evne til at forøge udnyttelsen af det naturlige lys med henblik på at erstatte eller supplere den kunstige belysning. Forsøgene blev udført i to sparsomt møblerede fuldskala rum, hvor det ene blev anvendt til forsøg, mens det andet var referencerum. Rummene var orienteret 15 grader syd-vest, med dimensionerne 3,2 m bredt, 6,75 m dybt og 3,1 m højt, hvor rummets reflektanser af gulv, loft og væg var konstante. Vinduerne var asymmetrisk placeret i facaden, og glassets dimensioner var 1,54 m højt og 2,16 m bredt. De indvendige belysningsstyrker, for tre dagslyssystemer, blev målt i vinduets symmetrilinje både på arbejdsplan og på loftsplan. Målingerne blev udført fra maj til november 1994 for følgende systemer:

- Indvendig og udvendig lyshylde med mat hvid og spejlende overflade
- Fem persienner med syv forskellige lamelpositioner
- Hvidt diffuserende gardin

Resultaterne af dagslysmålingerne

Målingerne i fuldskala forsøgslokalerne viste, at det var muligt at vurdere de afprøvede dagslyssystemer under virkelige himmelforhold. En delvis skyet himmel er den mest almindelige himmeltype i Danmark, men målingerne for denne himmel er udelukket i forsøgene på grund af de uendelige antal eksistererende himmelluminansfordelinger. Dagslyssystemerne blev derfor kun målt for en overskyet himmel og en skyfri himmel med direkte sol. Målingerne med direkte sol (sommer og efterår) viste, at der var behov for udvidede målinger for at afdække andre årstider (vinter), flere solpositioner, forskellige himmelforhold samt andre orienteringer. Yderligere er alle subjektive vurderinger kun udført af forfatteren, og har dermed en begrænset generel gyldighed. For at kunne give en generel vurdering af de kvalitative aspekter ved indførelse af "nye" teknologier i vindueskonstruktionen vil det være nødvendigt at anvende et større personpanel.

Baggrunden for at afprøve systemerne var som nævnt, at vurdere systemernes evne til at forøge dagslysudnyttelsen, forbedre dagslysfordelingen samt at afskærme rummet for direkte sol og høj himmelluminans. Lyshylder og persienner afskærmer og redirigerer direkte sol og diffust himmellys i rummet, mens et gardin totalt afskærmer for dette lys. Som en del af vurderingsgrundlaget for de givne himmelforhold blev alle systemer sammenlignet med et referencerum med almindelige vinduer. Hovedkriteriet for anvendelsen af dagslyssystemer i et klima domineret af skyet himmel er, at de ikke må blokere eller reducere diffust himmellys, men må være fleksible, dynamiske og kunne følge solens placering på himmelhvælvingen. Imidlertid viste målingerne for overskyede dage, at *alle de afprøvede dagslyssystemer* gav en reduceret belysningsstyrke på arbejdsplanet. Derudover viste de subjektive vurderinger, af og til, at den visuelle opfattelse af rummet med dagslyssystemerne (lyshylde, persienne) på en overskyet dag opfattedes lysere end referencerummet, selv om den målte belysningsstyrke viste, at dette ikke var tilfældet. Imidlertid vil ethvert system, som redirigerer eller reflekterer lys, reducere mængden af det lys som kommer ind i rummet på grund af uundgåelig tab ved passage af systemet. Den eneste mulighed for at forøge dagslysmængden, sammenlignet med et almindeligt vindue, er at anvende systemer som forøger udnyttelsen af det høje luminansområde omkring zenit.

Indvendige og udvendige lyshylder

Udgangspunktet for undersøgelsen af lyshylder, var en 0,5 m bred hylde placeret 2,0 m over gulvet. Overfladen af lyshylden var mat, hvid diffuserende og spejlende.

Resultaterne af målinger for en overskyet dag viste, at den indvendige lyshylde reducerede belysningsniveauet med 4-25%, mest i midten og mindst i den bagerste del af rummet. Den udvendige lyshylde reducerede belysningsniveauet med 10-45%, idet området tæt ved vinduet var afskærmet (45%).

For en skyfri himmel med direkte sol (sommer og efterår) var reduktionen i den bagerste del af rummet for den indvendige og udvendige diffuse lyshylde mindre (1-10%). Den indvendige, spejlende lyshylde (efterår) hævede belysningsniveauet i den bagerste del af rummet med 14-35%. Ved lave solhøjder kunne den direkte sol imidlertid trænge ind tæt ved vinduet og i midten af rummet, mellem lyshylden og loftet. Denne manglende afskærmning af den forreste del af rummet tilfredsstiller ikke et af funktionskravene og reducerer derfor anvendeligheden af lyshylder i danske erhvervsbygninger. Endvidere vil direkte sol på arbejdspladsen, eller på personen i rummet ofte medføre et behov for en supplerende afskærmning af solen, for eksempel persienner.

Den indvendige lyshylde medførte større utilfredshed sammenlignet med den udvendige, fordi udsynet og opfattelsen af rummet var påvirket af lyshyldens dominerende indvendige placering og størrelse. For at integrere en indvendig lyshylde må den derfor tilpasses vindueskonstruktionen. Subjektive vurderinger af blændingsproblemer for en overskyet eller klar himmel med direkte sol, viste ingen nævneværdig forskel mellem referencerummet og målerummet. Forklaringen skyldes lyshyldens simple udformning, og at den ingen virkelig effekt havde på at reducere synligheden af himlen. Det lysende reflekterede bånd fra den direkte sol på loftsplan og tilstødende vægge var direkte utilfredsstillende. Målinger viste at luminansen af det lysende bånd var ca. 30.000 cd/m^2 .

Persienner

Persiennerne blev afprøvet for syv lamelpositioner for følgende typer: spejlende med små og store lameller, hvid med medium lameller, hvid overside og spejlende underside (medium) og endelig for en sort persienne (medium).

Resultaterne af målinger for en overskyet dag viste, at persiennen i vandret lamelposition reducerede belysningsniveauet med 14-74%, mest tæt ved vinduet. Dette resulterede i en mere jævn lysfordeling mellem de lyseste og mørkeste områder af rummet. Desuden viste det reducerede belysningsniveau en ufavorabel afskærmningseffekt for en overskyet himmel. Dette understreger nødvendigheden af systemets bevægelighed og tilpasning til forskellige behov. Persienner i vandret lamelposition viste de mindste reduktioner i belysningsniveauet i den bagerste del af rummet. Opadrettede lameller (-30, -45 og -60°) transmitterede mere lys fra himlen direkte igennem persiennen. Dette forøgede belysningsniveauet tæt ved vinduet, således at reduktionen var mindre (20-68%) end ved den vandrette lamelposition. Drejedes lamellerne nedad (+30, +45 og +60°) kom lyset hovedsageligt fra jorden og reducerede dermed lysmængden ved vinduet med 75-97%.

For en skyfri himmel med direkte sol (efterår) var det kun den spejlende persienne i vandret lamelposition (store), som opfyldte formålet med at forøge belysningsniveauet (5-15%) i den bagerste del af rummet. Imidlertid gav den spejlende persienne en uacceptabel vinduesluminans på over 10.000 cd/m^2 for alle lamelpositioner ved direkte sol. Den har derfor begrænset anvendelighed som afskærmningssystem. Den hvide persienne med nedadrettede lameller (+45 og +60°) viste en effektiv og acceptabel afskærmning af den direkte sol og opfyldte dermed et af formålene. Den hvide persienne i vandret lamelposition reducerede belysningsniveauet i den bagerste del af rummet med 26-28%. Drejedes lamellerne opad (-30° og -45°) var reduktionen 31-46% og for nedadrettede lameller var den 52-84% i den bagerste del af rummet.

Persienner reducerede udsynet helt eller delvist, afhængigt af personens placering i rummet samt lamelhældningen. En af årsagerne til utilfredsheden med persiennerne var den visuelle "konflikt" ved øjets skiftende fokusering på baggrund (udsyn) og forgrund (persiennens lameller). Lameldrejninger hæmmede udsynet og forårsagede en forringelse af farvebestemmelsen på bladene af træet foran dagslyslaboratoriet. Denne forringelse erfaredes, men gentog sig ikke altid for de tilfælde, hvor himlen var overskyet med en opadrettet lamelposition på 30° og 45°. I en afstand af 3 m fra vinduet gav kun de store og medium lameller i vandret position et acceptabelt udsyn. Den spejlende persienne med små lameller, beregnet til at være placeret mellem to lag glas, viste en forøget utilfredshed. Dette gjorde sig også gældende for den vandrette lamelposition. Udsynet blev yderligere påvirket og reduceret af, at den direkte sol gav en kraftig lysende stribe på selve lamellerne med en luminans på over 100.000 cd/m^2.

For en himmel med høj luminans gav persiennen i vandret position forøget blænding fra vinduet, da lamellernes luminans var hævet og den samtidige adaptationsluminans reduceret. Ved opadrettede lameller var himlens synlighed øget og dermed også ubehaget af blænding, selvom lamelpositionen samtidig forøgede adaptationsluminansen i den forreste del af rummet. Afhængig af afstanden til observationspunktet, afskærmede de nedadrettede lameller synligheden af himlen og reducerede problemet med blænding. Ved direkte sol øgedes problemerne med reflekteret blænding, da direkte sol og en himmel med høj luminans reflekterede lyset direkte i synsfeltet. Størrelsen af reflekteret blænding var ubehagelig, selv i en afstand af 6 m med synsretning direkte mod vinduet, da det direkte sollys virkede synsnedsættende og gav tårer i øjnene. Yderligere virkede det reflekterede sollys visuelt distraherende, da persiennen reflekterede et lysbånd i en bestemt mønster både til loft og tilstødende vægge. Denne visuelle utilfredshed blev reduceret ved nedadrettet lamelhældning og ved anvendelse af diffuserende lameller.

Lyst diffuserende gardin

Det indvendige gardin var et lyst semi-transparent klæde med en afskærmningsfaktor på 0,45. Gardinet blev udvalgt, da det er den hyppigst anvendte afskærmning i kontorbygninger. Resultaterne af målingerne for en overskyet dag viste, at det indvendige gardin reducerede belysningsniveauet med 60-80%, mindst længst væk fra vinduet. For en skyfri himmel med direkte sol (efterår), var reduktionen 10-30% i den bagerste del af rummet. Problemet med blænding blev forøget, da luminansen på vinduet (gardinet) var 10.000 cd/m^2, adaptationsluminansen reduceret og fordi udsynet var elimineret.

Resultater af energianalyse

For at undersøge muligheder og konsekvenser af at erstatte kunstig belysning med dagslys, er det nødvendigt at udføre en integreret analyse af det naturlige lys, den kunstige belysning, reguleringsstrategier samt den termiske og energimæssige ydelse af bygninger ved f.eks. anvendelsen af tsbi3. Den simplificerede dagslysmodel i tsbi3 viste, at ved almindelige vinduesstørrelser og rumdimensioner, vil sollysfaktorerne ofte være tilstrækkelige nøjagtige for en integreret analyse. Formålet med denne del af opgaven var at undersøge mulighederne for at reducere energiforbruget til belysning og opvarmning ved anvendelse af kontrolsystemer til belysning eller ved at ændre på vinduesarealernes U-værdier.

Ud fra en model af en kontorcelle undersøgtes indvirkningen på den totale energibalance af samspillet mellem dagslys og den kunstige belysning for en typisk kontorbygning. Kontorcellen blev analyseret ved at anvende tre forskellige rudetyper, hvor vinduesarealet blev varieret mellem 15%, 25% og 40% af gulvarealet. Basismodellen havde en isoleringsstandard svarende til det nye Bygningsreglement (Boligministeriet 1995) og en 2-lags glasrude med lavemissionsbelægning (U-værdi 1,6 W/m^2 K). Desuden undersøgtes en almindelig 2-lags termorude (2,8 W/m^2 K) som reference til Bygningsreglementet fra 1982, samt en vacuumrude (0,8 W/m^2 K) der er brugt som eksempel på at imødekomme evt. fremtidige skærpelser i bygningsreglement. I analysen er den procentvise forøgelse eller reduktion vist i relation til basiskontorcellen med et 15% vinduesareal med lavemissionsglas og den kunstige loftsbelysning, som altid var tændt i arbejdstiden. Den kunstige belysning var styret efter dagslysniveauet på arbejdsplanet i et reference punkt, henholdsvis 3 m og 5.4 m fra vinduesvæggen. Det ønskede belysningsniveau for de udvalgte referencepunkter var 200 lux. Som afskærmning blev lyse nedadrettede persienner aktiveret, når strålingen som transmitteredes gennem glasset, var højere end 150 W/m^2.

Simuleringen viste (15% vinduesareal), at ved brug af dagslys som arbejdspladsbelysning kan der opnås besparelser på 27% til 62% af den kunstige loftsbelysning. Med et referencepunkt i midten af rummet (3 m) vil der med en tænd/sluk og en kontinuerlig reguleringsstrategi være et besparelsespotentiale på henholdsvis 50% og 62%. Selvom dagslysniveauet er mindre bagerst i rummet, vil det naturlige lys i et referencepunkt 5.4 m fra vinduet alligevel give et besparelsespotentiale på 27-46% af elforbruget til belysning. Resultaterne understreger nødvendigheden af at den kunstige belysning reguleres for at kunne realisere de potentielle besparelser som ellers ville være tabt. Imidlertid vil en strategi for kontrol af belysning reducere den kunstige loftsbelysning, men samtidig forøge energiforbruget til opvarmning på grund af den reducerede interne varmelast fra elbelysningen. Hvis forøgelsen af opvarmningsbehovet tages i betragtning vil den totale energibesparelse blive reduceret til 12-19%.

Øges vinduesarealet til henholdsvis 25% og 40% af gulvarealet, forøges transmissionstabet og opvarmningsforbruget, men samtidig også mængden af det naturlige lys. Med en tænd/sluk- eller kontinuerlig regulering (3 m) er besparelsespotentialet henholdsvis 63% og 69% (25% vinduesareal) og henholdsvis 66% og 71% (40% vinduesareal). Hvis forøgelsen af opvarmningsbehovet tages i betragtning, vil den totale energibesparelse blive reduceret til henholdsvis 12-13% (25% vinduesareal) og 2% (40% vinduesareal). Det reducerede besparelsespotentiale ved forøgelsen af vinduesarealet indikerer, at en "optimal" vinduesstørrelse kan bestemmes, men resultaterne viser yderligere, at det er absolut nødvendig at udstyre bygningen med et kontrolsystem som tilpasser og reducerer unødvendig brug af elektrisk belysning. Ved anvendelse af et "omkostningsindeks" på energiforbruget baseret på brug af naturgas til opvarmning viste simuleringerne en forøgelse i besparelsespotentialet på 23-30%. Dette understreger at brugen af "omkostningsindeks" (eller miljøindeks) kan have stor betydning for bestemmelsen af den optimale vinduesstørrelse. Forbedredes U-værdien af vinduet (0,8 W/m^2 K, vacuumvindue) viste simuleringerne, at det samlede opvarmnings- og belysningsforbrug gav en forøget energibesparelse på 33% til 39% for de undersøgte vinduesarealer, mens omkostningsindekset gav en besparelse på 42-48%. Det må understreges, at disse energianalyser kun er gældende for den specifikke kontormodel, og at resultaterne derfor ikke ukritisk kan overføres til andre situationer eller gøres generelt gældende.

Simuleringerne viste, at en total reduktion på 50% af den energi som er produceret af fossile brændstoffer, beskrevet i Brundtland Rapporten: "Vår fælles fremtid," og i den danske energihandlingsplan: "Energi 2000", kan opfattes som et ambitiøst, men ikke urealistisk mål. Imidlertid er disse besparelsespotentialer kun opnået ved simulering af en optimal situation og ikke ud fra en faktisk undersøgelse. I praksis vil andre forhold spille ind og forudsætningerne variere, hvilket understreger nødvendigheden af en udvidet undersøgelse af styringen af den kunstige belysning og reguleringssystemers optimale placering i rummet.

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Appendix A. Local solar radiation geometry

In the literature, the sun is usually described as a huge fusion reactor, where light atoms are fused into heavier atoms and in the reaction process energy is emitted by the sun. Radiation emitted from the sun's surface is usually characterised as a blackbody obeying Planck's law of emitting electromagnetic radiation. Of the emitted solar radiation from the sun, roughly 98% reaches the outer edge of the earth's atmosphere, also called extraterrestrial radiation [Robinson 1966]. The extraterrestrial radiation has an almost fixed intensity called the *solar constant* $E_{e,o}$ defined as *irradiance produced by the extraterrestrial solar radiation on a surface perpendicular to the suns's rays at the mean earth-sun distance equal to 1367* W/m^2 [CIE 1987]. The broken line in Figure A.1 illustrates the spectral distribution of extraterrestral radiation for a fixed solar constant.

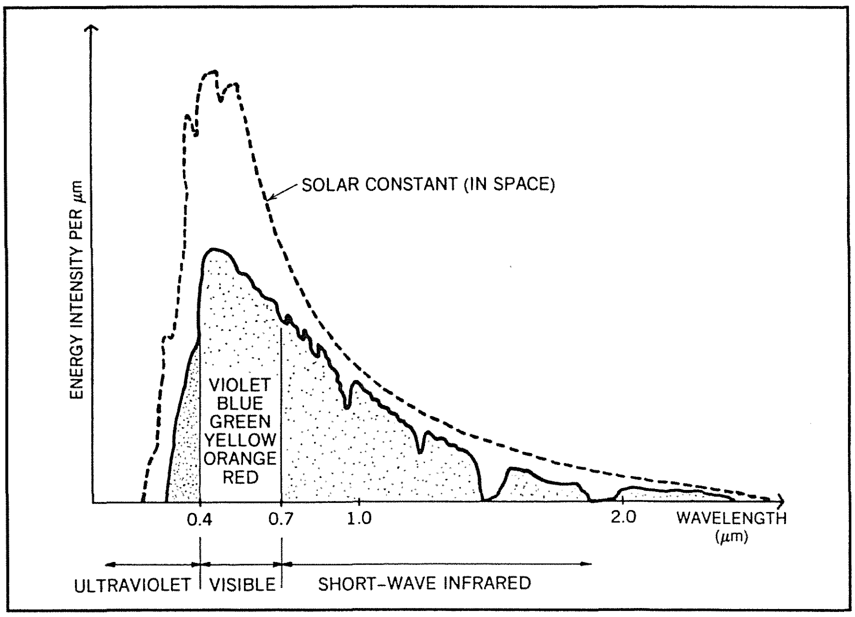

Figure A.1 The solar spectrum at the earth's surface consisting of 52% visible, 44% short-wave infrared and 6% ultraviolet radiation [reprinted from Lechner 1991].

However, discrepancies exist in the intensity of extraterrestrial radiation emitted by the sun due to periodic variations related to sunspots (less than ± 1.5%) and the earth-sun distance. The orbit of the earth is elliptic with a variation in sun-earth distance approximately ± 1.7%, since the earth revolves around the sun due to the eccentricity of the earth's orbit. The seasonal changes in solar radiation are a result of the sun-earth distance, where the mean sun-earth distance is equal to $1.495 \bullet 10^{11}$ m [Duffie 1991], and the earth's axis of rotation is tilted 23.45° (remains fixed) to the plane of the elliptical orbit. The fixed tilt of the earth's axis causes the northern hemisphere to face the sun in June with summer solstice (June 21), when the North Pole points most nearly toward the sun, and winter solstice (December 21) when the North Pole is at it's greatest distance from the sun [Lechner 1991]. The spring and fall equinoxes (March 21 and September 21) are defined as the days of the year of equal nighttime and daytime with sunrise and sunset due east and west respectively.

Solar radiation received at the outer edge of the earth's atmosphere, extraterrestrial radiation, has an almost fixed intensity called the *solar constant* G_{sc} equal to 1367 W/m^2 [CIE 1987] (the broken line illustrated in Figure 2.1) defined as *irradiance produced by the extraterrestrial solar radiation on a surface perpendicular to the suns's rays at the mean earth-sun distance* [845-09-78, CIE 1987]. Discrepancies exist in the intensity of extraterrestrial radiation emitted by the sun due to periodic variations related to sunspots (less than ± 1.5%) and/or the earth-sun distance. The orbit of the earth is elliptic with a variation in sun-earth distance approximately 3.3% since the earth revolves around the sun due to the eccentricity of the earth's orbit. The variation of sun-earth distance results in a small annual variation in the intensity of extraterrestrial radiation (see eq. A.1).

$$G_{on} = G_{sc} \cdot \left(1 + 0.033 \cos \frac{360 \cdot n}{365}\right) \qquad \text{A.1}$$

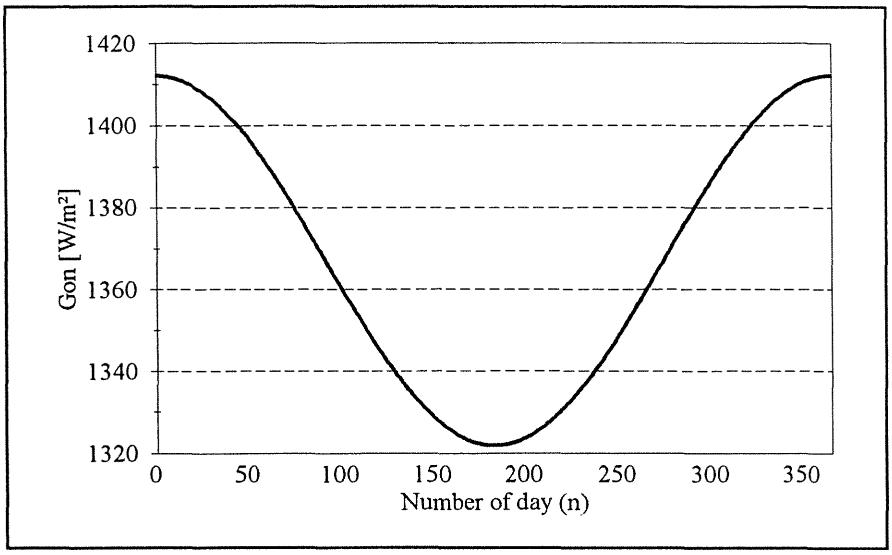

Figure A.2 Variation of extraterrestrial solar radiation with time of year [Solar Constant G_{sc} = 1367 W/m²].

Equation A.1 indicates the annual variation with time over the year in extraterrestrial radiation (± 3 %) where G_{on} is the extraterrestrial radiation measured on a plane normal to the radiation on the *n*th day of the year for a solar constant G_{sc}. The intensity of solar radiation follows the inverse square law, where extraterrestrial radiation measured on a plane normal to the radiation varies from 1412 W/m² Januar 1 and 1323 W/m² July 5 for a solar constant G_{sc} equal to 1367 W/m² [ASHRAE 1992].

The local geometric correlation with direct solar radiation striking a plane of any particular orientation is regular and predictable, since the sun's apparent motion and its angular relationship determine the intensity of the direct normal component. Consequently, a surface will receive more direct solar radiation if the receiving surface is normal to the angle of incidence. Solar time defines the relationship between sun angles based on the apparent angular motion of the sun across the sky vault and the local time. The sun will always be due south at solar noon, which is 12 o'clock noon solar time, when the sun crosses the meridian (north-south line). Inevitable corrections have to be applied to convert solar time into local apparent time for three reasons; daylight saving time, an equation of time which allows for irregularities in the actual length of the solar day throughout the year, and the longitude of the building site in relation to the meridian [Hopkinson 1966, Balcomb 1992, Lechner 1991]. Solar time is related to standard time by eq. A.2 [Duffie 1991]:

$$\textit{solar time} = \textit{standard time} + 4 \cdot (L_{st} - L_{loc}) + E\ (-\ \textit{daylight saving time}) \qquad \text{A.2}$$

where L_{st} standard meredian for the local time zone
L_{loc} longitude of the location in question in degrees west
E Equation of the time in minutes described by *the perturbation in the earth's rate of rotation which affects the time the sun crosses the meridian* [Duffie 1991]:

$$E = 9.87 \cdot \sin 2B - 7.53 \cdot \cos B - 1.5 \cdot \sin B \qquad \text{A.3}$$

where B for n = day of the year (1 ≤ n ≤ 365) is:

$$B = \frac{360 \cdot (n - 81)}{364} \qquad \text{A.4}$$

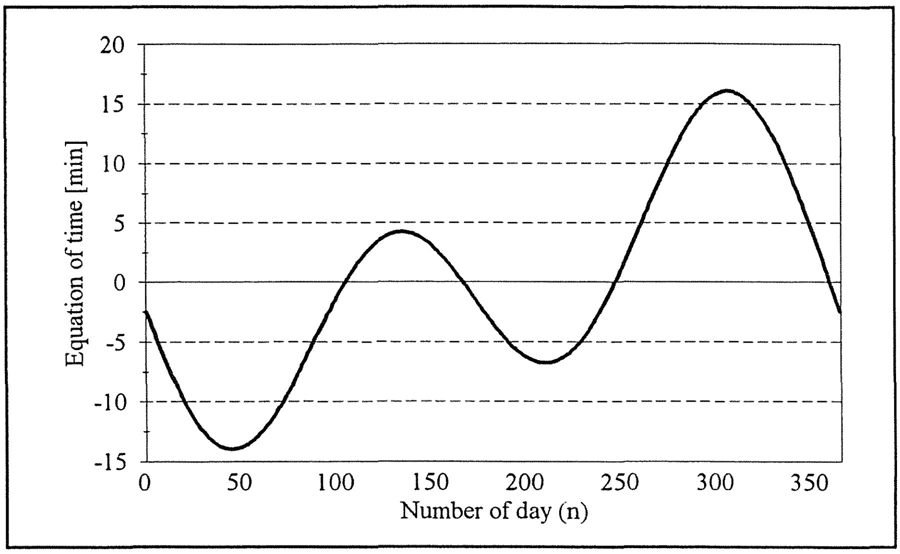

Figure A.3 The equation of time E in minutes, as a function of time of year.

The seasonal changes in solar radiation are a result of the sun-earth distance, where the mean sun-earth distance is equal to $1.495 \cdot 10^{11}$ m [Duffie 1991], and the earth's axis of rotation is tilted 23.45° (remains fixed) to the plane of the elliptical orbit. This cause solar radiation striking the earth to be parallel to the orbit plane providing continuous changes thoughout the year to the incident angle at which the rays from the sun strike a horizontal surface on earth (the solar declination δ). The fixed tilt of the earth's axis causes the northern hemisphere to face the sun in June with summer solstice (June 21), when the north pole points most nearly toward the sun, and winter solstice (December 21) when the north pole is pointing farthest away from the sun [Lechner 1991]. The spring and fall equinoxes (March and September 21) are defined as the day of the year of equal nightime and daytime with sunrise and sunset due east and west respectively. The solar declination δ is the angle between the earth-sun line and the earth's equatorial plane estimated by eq. A.5:

δ *Declination [Cooper 1969], the angular position of the sun at solar noon (i.e., when the sun is on the local meridian) with respect to the plane of the equator, north positive* [Duffie 1991] ($-23.45° \leq \delta \leq 23.45°$). The declination is +23.45° at the summer solstice and, 0° at the equinoxes and -23.45 at the winter solstice.

$$\delta = 23.45 \cdot \sin\left[360 \cdot \frac{284 + n}{365}\right] \qquad \text{A.5}$$

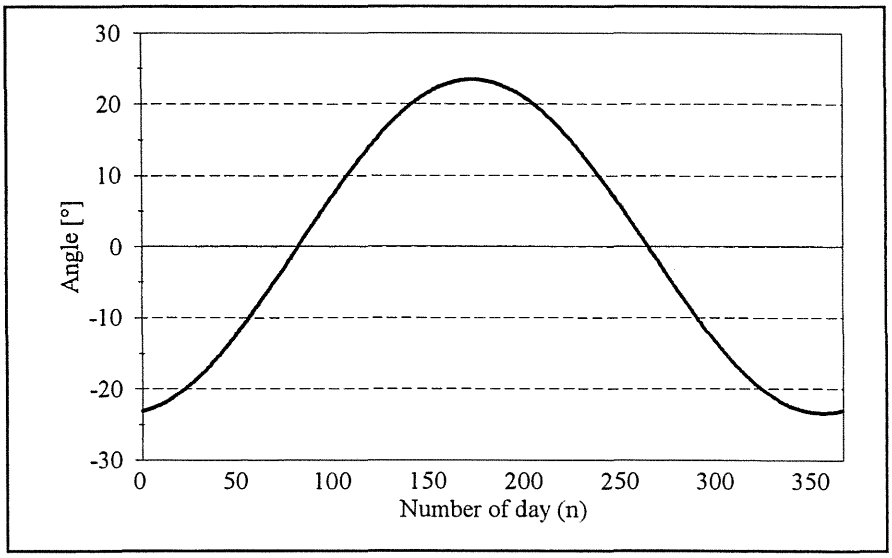

Figure A.4 Variation of the declination angle with time of year.

A sun position exactly on the meridian (solar noon) produces a solar azimuth equal to 0°, also the south-north line. For any particular orientation at any local time and date (declination) related to a specified longitude and latitude, incoming direct solar radiation can be described in terms of several angles [Petersen 1982, Svendsen 1985, Duffie 1991, Jensen 1993]. These angles and the relationships between them are as follows [reprinted from Duffie 1991] (see Figure A.5):

ϕ Latitude is , that is, the angular location north or south of the equator, north positive. ($-90^\circ \leq \phi \leq 90^\circ$).

γ_t Slope, that is, the angle between the plane surface in quastion and the horizontal. ($0^\circ \leq \gamma_t \leq 180^\circ$ where, $\gamma_t > 90^\circ$ means the surface has a downward facing component)

α_k Surface azimuth angle, that is, the deviation of the projection on a horizontal plane of the normal to the surface from the local meredian, with zero due south (sometimes north is zero), east negative, west positive. ($-180^\circ \leq \alpha_k \leq 180^\circ$)

$$\sin\alpha_k = \frac{\cos\delta \cdot \sin\omega}{\cos\gamma_s} \tag{A.6}$$

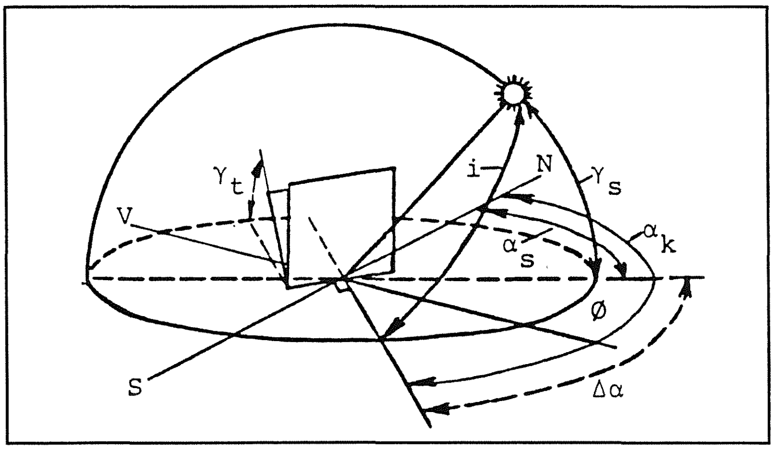

Figure A.5 Slope γ_t - surface azimuth α_k - solar azimuth α_s - solar altitude angle γ_s - angle of incidence i.

ω Hour angle (see A.6), that is, the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour (bearing angle), morning negative, afternoon positive.

$$\omega = \frac{\pi}{12} \cdot t \tag{A.7}$$

i Angle of incidence, that is, the angle between the beam radiation on a surface and the normal to that surface ($0^\circ \leq i \leq 90^\circ$). Equation A.8 relates the angle of incidence of beam radiation combined with the other angles:

$$\begin{aligned}\cos i = {} & \sin\delta \cdot \sin\phi \cdot \cos\gamma_t - \sin\delta \cdot \cos\phi \cdot \sin\gamma_t \cdot \cos\alpha_k + \cos\delta \cdot \cos\phi \cdot \cos\gamma_t \cdot \cos\omega \\ & + \cos\delta \cdot \sin\phi \cdot \sin\gamma_t \cdot \cos\alpha_k \cdot \cos\omega + \cos\delta \cdot \sin\gamma_t \cdot \sin\alpha_k \cdot \sin\omega\end{aligned} \tag{A.8}$$

i_z Zenith angle is the angle subtended by a vertical line to the zenith (i.e., the point directly overhead) and the line of sight to the sun ($0^\circ \leq i_z \leq 90^\circ$). For a horizontal surface the angle of incidence is equal to the zenith angle (see eq. A.10):

$$\cos i_z = \cos\delta \cdot \cos\phi \cdot \cos\omega + \sin\delta \cdot \sin\phi \tag{A.9}$$

γ_s Solar altitude angle is the angle of elevation above the horizon measured to the position of the sun ($90^\circ - i_z$) by eq. A.10:

$$\sin\gamma_s = \cos\delta \cdot \cos\phi \cdot \cos\omega + \sin\delta \cdot \sin\phi \tag{A.10}$$

α_s Solar azimuth angle is the angular displacement from south of the projection of the beam radiation on the horizontal plane ($-180^\circ \leq \alpha_s \leq 180^\circ$) with a bearing angle moving 15° per hour since the sun travels 360° laterally in 24-hours. For north or south latitudes between 23.45° and 66.45°, α_s will be between 90° and -90° for days less than 12 hours long; for days with more than 12 hours between sunrise and sunset, α_s will be greater than 90° or less than -90° early and late in the day when the sun is north of the east-west line in the northern hemisphere. Thus, to calculate α_s, its necessary to know in which quandrant the sun will be. This is determined by the relationship of the hour angle ω to the hour angle ω_{ew}, when the sun is due west (or east). Algorithm for α_s is defined in terms of α'_s, a pseudo surface azimuth angle in degrees in the first and fourth quandrant (see eq. A.11 [Duffie 1991]).

$$\alpha_s = C_1 \cdot C_2 \cdot \alpha'_s + C_3 \cdot \left(\frac{1 - C_1 \cdot C_2}{2} \right) \cdot 180 \qquad \text{A.11}$$

where pseudo surface azimuth angle is (in degrees):

$$\sin \gamma'_s = \frac{\sin \omega \cdot \cos \delta}{\sin \theta_Z}$$

or A.12

$$\tan \gamma'_s = \frac{\sin \omega}{\sin \delta \cdot \cos \omega - \cos \theta \cdot \tan \delta}$$

and the coefficients are:

$$C_1 = \begin{cases} 1 & \text{if } |\omega| \leq \omega_{ew} \\ -1 & \text{if } |\omega| > \omega_{ew} \end{cases}$$

$$C_2 = \begin{cases} 1 & \text{if } (\theta - \delta) \geq 0 \\ -1 & \text{if } (\theta - \delta) < 0 \end{cases} \qquad \text{A.13}$$

$$C_3 = \begin{cases} 1 & \text{if } \omega \geq 0 \\ -1 & \text{if } \omega < 0 \end{cases}$$

and the hour angle ω_{ew}:

$$\cos \omega_{ew} = \frac{\tan \delta}{\tan \phi} \qquad \text{A.14}$$

ω_s Sunset hour angle, that is, the hour angle of the sun at sunset defined by eq. A.15:

$$\cos \omega_s = - \frac{\sin \phi \cdot \sin \delta}{\cos \phi \cdot \cos \delta} = - \tan \phi \cdot \tan \delta \qquad \text{A.15}$$

Φ Profile angle, that is, the projection of the solar altitude angle on a vertical plane perpendicular to the plane in question, or expressed as the angle through which a plane that is initially horizontal must be rotated around an axis in the plane of the surface in question in order to include the sun. The solar altitude angle γ_s (i.e. $\angle$ BAC), and the profile angle Θ (i.e. $\angle$ DEF), for the surface is illustrated in Figure A.6. Note the solar altitude and profile angle are the same when the sun are in a plane perpendicular to the surface (e.g. at solar noon for a surface with a surface azimuth angle 0° or 180°). In US publications, the vertical shadow angle is usually referred to as the profile angle and can be found by eg. A.16:

$$\tan \Phi = \frac{\tan \gamma_s}{\cos (\alpha_s - \alpha_k)} \qquad \text{A.16}$$

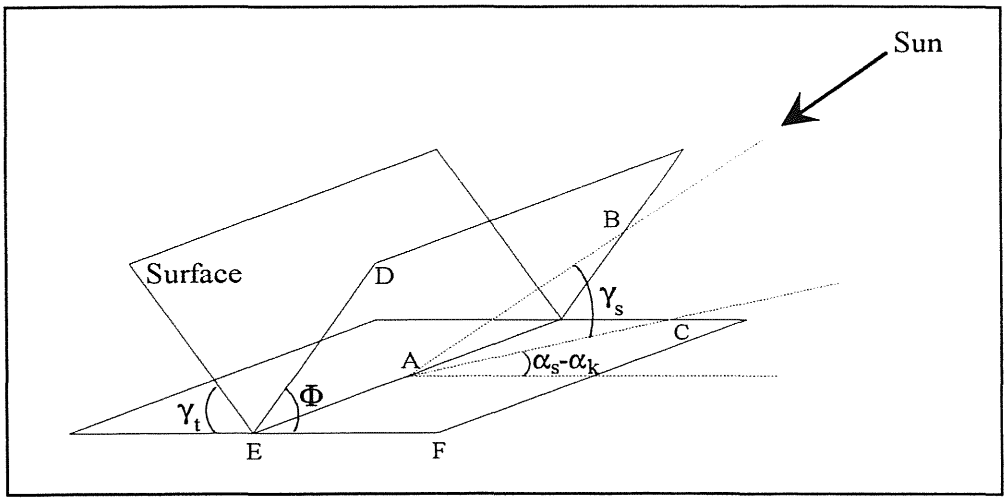

Figure A.6 The solar altitude angle γ_s *(i.e.* $\angle$ *BAC), and the profile angle* Θ *(i.e.* $\angle$ *DEF), for the surface.*

Appendix B. Simplified Glare Calculation of DGI and Transformation

The aim of a good daylight design is first, to provide fully sufficient light for efficient visual performance, and second, to ensure a comfortable and pleasing environment appropriate to its purpose. The comfort aspect of a daylight design is closely related to the problem of glare [Hopkinson 1966]. Generally glare can be described as a subjective phenomenon caused by the magnitude of visible noise interferring with the perception of visual information due to an uncomfortably bright source of light in the field of vision. Measuring the magnitude of glare is only possible by characterisations and assessments from the observer involved, together with the physical factors determining the magnitude of the sensation. The CIE defines glare as the *condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable contrast* [CIE 1987].

In the early decades of this century, investigations have been conducted to reveal the magnitude of experienced luminaires appearing too bright in the field of vision and causing visual discomfort [Perry 1993c]. Most of the recognised experimental research on subjective glare sensation was conducted in the 1940-50s at the Building Resarch Establishment BRE (England) and by Luckiesh and Guth (USA). In both experiments, trained observers were used to assess the sensation of glare. It resulted in an index describing the subjective assessments of the degree of discomfort caused by a glare source subtending a solid angle (ω_s) of $2.7\cdot10^{-4} \leq \omega_s \leq 2.7\cdot10^{-2}$ sr. A glare index describes the subjective magnitude of glare discomfort with high values illustrating uncomfortable or intolerable sensation of discomfort. It also provides the designer with an indication of how to control and limit glare discomfort. However, most of the equations developed do not (unfortunately) predict the sensation of glare from daylight accurately [Chauvel 1982]. At the moment, only the Cornell glare index DGI predicts the combined effect of the physical values of size and position of windows (large glare source), sky and background (adaptation) luminance, the observer's line of sight, distance and position in relation to the window etc. The literature produces a number of equations for a single glare source, but all these equations can simply be described by eq. B.1:

$$\textit{Glare sensation} = \frac{(\textit{Luminance of the glare source})^m \cdot (\textit{angular subtense of the glare source at the eye})^n}{(\textit{Luminance of the background})^x \cdot (\textit{deviation of the glare source from the line of sight})^y} = \frac{L_s^m \cdot \omega_s^n}{L_b^x \cdot p^y} \qquad \text{B.1}$$

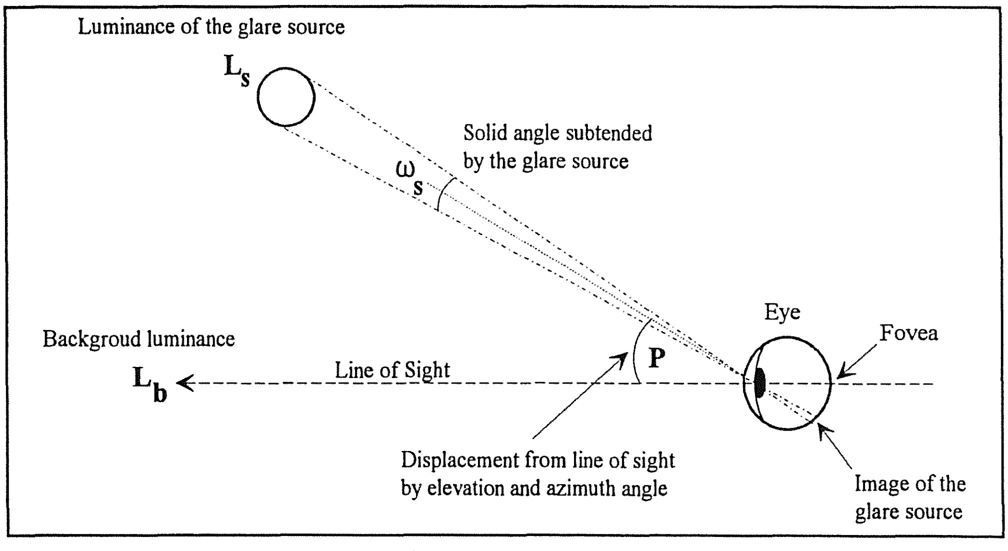

Figure B.1 A simplified illustration of the parameters influencing the sensation of discomfort glare experienced (after [CIE 1983]).

Figure B.1 illustrates the parameters influencing the sensation of discomfort glare for a simplified diagram of the eye. The image on the fovea is formed by the the object in the line of sight and the image formed by the glaring source in a different location on the retina [CIE 1983]. Equation B.1 shows that, increasing the luminance of the glare source L_s and the solid angle subtended by the source (ω) while decreasing the elevation angle and azimuth angle (P) to the centre of vision, will increase the sensation of glare experienced. However, increasing the background luminance L_b would reduce the sensation of glare, supporting intelligent design and dimension of daylight windows. The simplicity of this analysis is not valid since the different factors can rarely be varied independently.

The Cornell glare index: DGI

The Cornell glare index is a modification of the BGI index, predicting glare from a large source (window). The study was conducted at the BRE and Cornell University (USA) [Hopkinson 1963 a-b & 1970-71 & 1972, Chauvel 1982, Boubekri 1992, Iwata 1992]. Evaluation of the Cornell glare index conducted by Cauvel concluded that *discomfort glare from a single window (except for a rather small one) is practically independent of size and distance from the observer but critically dependent on the sky luminance* [Chauvel 1982]. The degree of glare caused by any large glare source can be expressed by (eq. B.2):

$$DGI = 10 \log_{10} 0.478 \sum_{i=1}^{n} \frac{L_s^{1.6} \cdot \Omega^{0.8}}{L_b + 0.07 \cdot \omega_s^{0.5} \cdot L_s} \qquad \text{B.2}$$

where	L_s	Luminance of the glare source [cd/m^2]
	L_b	Luminance of the background without the luminance of the glare source [cd/m^2]
	ω_s	Solid angle of the source seen from the point of observation [steradian] (see Figure B.3)
	P	Guth's position index, expressing the change in discomfort glare experienced relative to the azimuth and elevation of the position for the glare source and the observer's line of sight
	Ω	Solid angle subtended by the source, modified for the position of the light source with respect to the field of view and Guth's position index P [steradian] (see Figure B.3).

$$\Omega = \int_{\omega_s} \frac{d\,\omega_s}{P^2} \qquad \text{B.3}$$

n number of glare sources

Values of ω_s and Ω shown diagrammatically
Equation 4.3 can be used to estimate the glare constant for a vertical window. For a vertical window, the ratio of the height *H* of the window to the distance *d* from observation point (H/d) can be determined from Figure B.2. *H* is the height of the window above or below the horizontal plane through the eyes. The ratio of the length *L* to the distance *d* from observation point (L/d) can be determined from Figure B.2. *L* is the distance between the direction of view and the right or the left outermost vertical edge of the window. The view is horizontal and perpendicular to the facade from a distance *d* from the observation point opposite the centre of the window or windows.

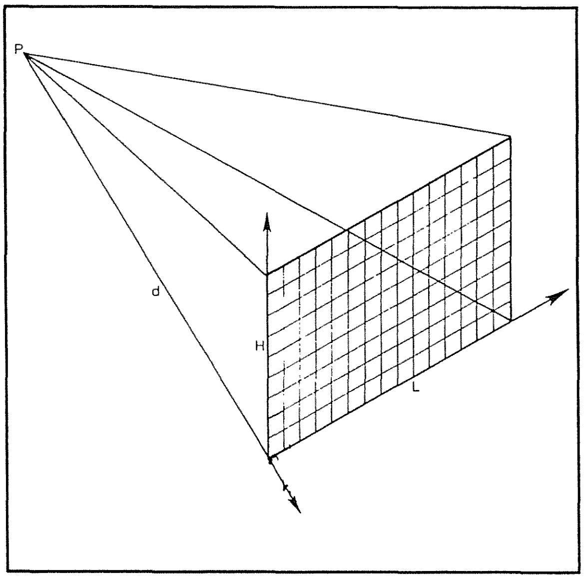

Figure B.2 H/d and L/d for verical windows [reprinted from Robbins 1986].

The vaues of ω_s and Ω can be determined from Figure B.3.

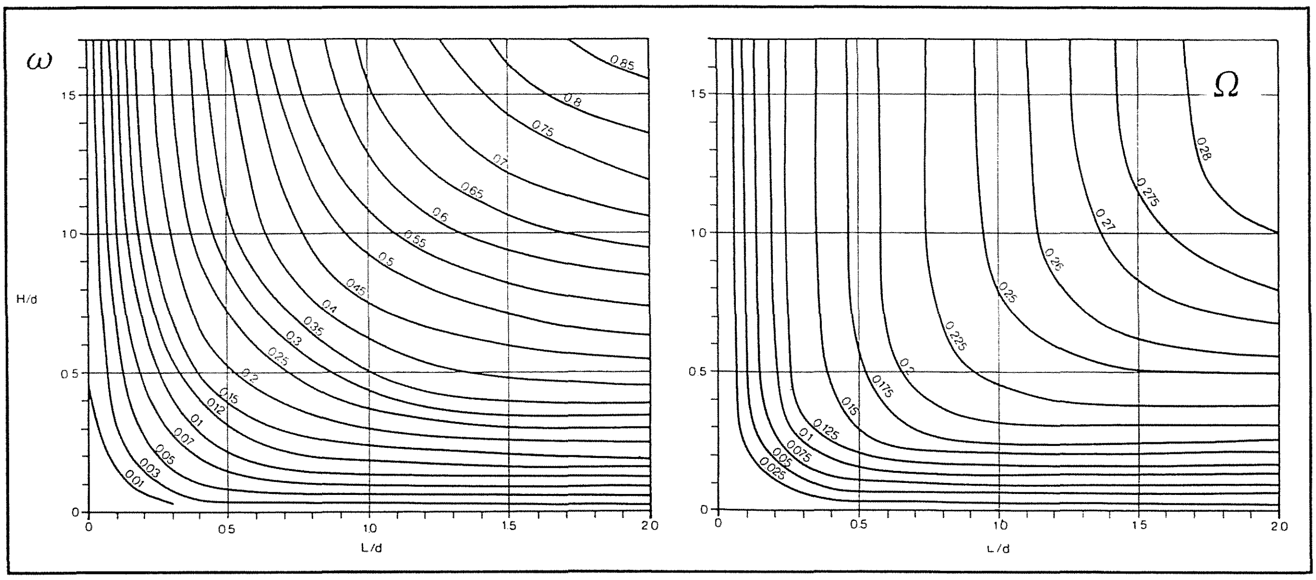

Figure B.3 ω_s and Ω values plotted against the ratio of H/d and L/d [Reprinted from Robbins 1986].

Discomfort glare number transformation

For analysis, on a statistical basis, this necessitates knowledge of the connexion between the different glare indexes.

DGI and BGI, CGI, UGR (glare index)

$$DGI = \frac{2}{3} \cdot \left(Glare\ Index + 14 \right) \quad for\ values \le 28 \tag{B.4}$$

where the glare index is BGI, CGI, UGR

DGR and VCP

$$VCP = \begin{cases} 279 - 110 \cdot \log DGR & if \;\; 55 \le DGR \le 200 \\ 279 - 110 \cdot \log DGR + 350 \cdot (\log DGR - 2.08)^5 & if \;\; DGR \rangle \, 200 \end{cases} \tag{B.5}$$

BGI, CGI, UGR and VCP

The relationship between the VCP and BGI, CGI and UGR is "statistical" since the basic formulations differ.

$$VCP = 124 - 4\ GI \qquad if \;\; 10 \le BGI,\ CGI,\ UGR \le 26 \tag{B.6}$$

For a VCP equal to 50, also borderline between comfort and discomfort (BCD) this produces a BGI, CGI or UGR equal to 18.5.

BRS-GI og DGR

$$10 \log DGR = 14.1 + 0.36 \cdot BRS - GI \tag{B.7}$$

The DGR system was used to define the percentage of people assessing an installation to be at or more comfortable than the borderline between comfort and discomfort, also called the visual comfort probability (VCP) [Guth 1959 & 1963 & 1966, MacGowan 1969, CIE 1983]. High levels of VCP predict increasing acceptability of the glare performance from an installation. The VCP glare scale is inverted relative to the BGI scale [Perry 1993 c]. The scale defined by the British system demonstrate that one glare index unit is the least detectable step and three glare index units are the normally acceptable step [CIE 1992]. However, some of the criticisms to the experiments conducted at BRE and by Luckiesh and Guth are its applicability to ordinary observers, the time of adaptation to the experimental conditions before assessments of discomfort, the "leading" nature of the instructions given and the criterion technique of subjective appraisal [Hopkinson 1963, Boyce 1981]. The criticisms regarding the criterion technique are simply that observers tend to match the middle of the rating scale with the middle of the conditions experienced [Poulton 1977, Boyce 1981]. Although the recognised empirical models of discomfort glare provide the designer with an indication of advice, they are based on lighting technology current at the time of developments, "reducing" their applicability of glare calculations of today's lighting technology, working conditions and activities (VDU). Table B.1 shows for different glare indexes the magnitude of discomfort glare corresponding to the visual comfort probability (VCP).

Table B.1 Comparison of the corresponding magnitude of discomfort glare experienced for different glare indexes with the visual comfort probability (VCP).

Corresponding degree of Glare	**BGI** **CGI** **UGR**	**DGI**	**DGR** **&** **M**	**Comfort** **VCP** **%**
No Glare			< 20	
Unnoticeable	< 10	< 16	35	95
Just imperceptable	10	16	50	87
Acceptable but not imperceptable	13	18	65	75
Just acceptable	16	20	90	64
BCD	18.5	22	**120**	**50**
Just uncomfortable	22	24	220	20
Uncomfortable	25	26	300	11
Just intolerable	28	28	400	5
Intolerable			700	

Appendix C. Reflection Properties

Measurements of reflection factors in the daylight laboratory for a surface have been conducted by the luminance and illuminance method.

The luminance method

The luminance measurements consist mainly of a comparison between two measured luminance values. To measure the reflection factor, the Hagner photometer (which may be placed on a tripod) was pointed towards the surface whose reflection factor was to be measured, and the luminance value was noted. The same procedure was used with a matt white disc with an accurately known reflection factor (ρ = 0.937). Cautiousness was accounted for so the illuminance and measurement geometry remained unchanged. The measurement method described above applies to matt surfaces. Polished surfaces must be measured with care, as a mirror reflection can distort the results completely.

The reflection factor can now be determined by:

$$\rho_x = \frac{\rho_R \cdot L_x}{L_R} \qquad \text{C.1}$$

where
ρ_x The reflection factor of the examined surface
ρ_R The reflection factor of the reference surface [rho$_R$ = 93.7%]
L_x The luminance of the examined surface [cd/m^2,1°]
L_R The luminance of the reference surface [cd/m^2,1°]

The illuminance method

The illuminance measurements are a comparison between two measured illuminance values using a remote detector, connected to the photometer by a flexible lead. To measure the reflection factor, the detector was placed at the surface and the illuminance value was noted. The detector was then pointed towards the surface at a distance of 30 cm and the illuminance value was noted. The measurements should only be taken as an estimation of the reflection factor.

The reflection factor can now be determined by:

$$\rho = \frac{E_r}{E_f} \qquad \text{C.2}$$

where
ρ The reflection factor of the examined surface
E_f The illuminance value at the examined surface
E_r The illuminance value at a distance of 30 cm with the detector pointed towards the examined surface

Table C.1 Average measured values of reflection factors with the illuminance and luminance methods, where N is the total number of measurements.

Surfaces	**Illuminance Method**		**Luminance Method**	
	N	[%]	N	[%]
Wall left (White curtain)	5	60	7	63
Wall left (Black curtain)	5	4	2	4
Wall right (White curtain)	3	41	3	82
Rear Wall (White curtain)				
Front wall Left (Black paint)	3	16	2	5
Front wall below (Grey paint)	3	38	2	42
Floor	3	9	2	8
Roof	3	86	5	89
Table	3	15	5	12

This Ph.D. thesis presents the qualitative and quantitative consequences of full-scale measurements on two daylighting systems, *lightshelf* and *Venetian blinds*. The systems were investigated to assess their ability to increase daylight penetration and improve daylight distribution in the interior, aiming at increased utilisation of daylight in order to supplement and replace artificial lighting. The visual quality is assessed only by subjective evaluations of the luminous environment, luminance distributions in the interior and glare problems. This thesis does not pretend to answer or solve all the benefits and difficulties regarding use of daylight in office buildings, but it is hoped that the report will provide daylight conscious building design in forthcoming non-domestic buildings.