A METHODOLOGY FOR DETAILED CALCULATION OF ILLUMINANCE LEVELS AND LIGHT DIMMING FACTORS IN A ROOM WITH MOTORIZED BLINDS INTEGRATED IN AN ADVANCED WINDOW

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ABSTRACT

A Methodology for Detailed Calculation of Illuminance Levels and Light Dimming Factors in a Room with Motorized Blinds Integrated in an Advanced Window

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Utilisation of daylight in buildings may result in significant savings in electricity consumption for lighting while creating a higher quality indoor environment. The benefits in terms of higher productivity and reduced absenteeism of office workers probably exceed the significant energy savings. Additional energy savings are also realised during the cooling season, when reduction of internal heat gains due to electric lighting results in a corresponding reduction of cooling energy consumption.

This study presents a simulation of an office space with an advanced window with integrated motorized venetian blinds between the panes. The methodology developed consists of the following steps:

1. The transmittance characteristics of the window with the shading device are determined as a function of blind tilt angle, solar incidence angle and sky conditions from full scale experimental measurements in an outdoor test room. Thus, they may be employed for any orientation and location and utilised both for control and design. In control, they would allow the prediction of incoming daylight with just one exterior sensor on each building façade.

2. The illuminance distribution on the work plane due to daylight is determined, based on detailed radiosity analysis including calculation of all necessary form and configuration factors. At the same time, the optimal blind tilt angle is selected in order to avoid glare, allow maximum view to the outside and transmit the maximum possible amount of daylight in the interior space.
3. The electrical light level required to achieve the necessary total illuminance level on the work plane is computed and light dimming levels are established for all the lights in the space throughout the year.
4. Energy savings from reduced utilisation of electric lights are estimated. Savings of over 75% are computed for a typical office space. The shading device and light dimming control algorithm may be implemented in an intelligent building automation system in conjunction with simultaneous control of HVAC systems, in order to minimize energy consumption while maintaining good human comfort.

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NOMENCLATURE

A *surface area*

c *optical atmospheric extinction coefficient*

$C_{dA\text{-}S1}$ *configuration factor between differential surface dA (point) and surface* S_1

$dim_{1,2}$ *dimming factors for luminaire 1,2*

E *illuminance*

F_{ij} *form factor between surfaces i, j*

G *glare index*

h *hour angle*

i *iteration/surface index*

j *surface index*

L *luminance*

$L_{1,2}$ *luminaire 1,2*

M *luminous exitance*

m *relative optical air mass*

n *day number in the year*

r *blind width/distance between blinds*

a *solar altitude*

β *blind tilt angle*

γ *surface solar azimuth*

δ *solar declination angle*

θ *angle of incidence*

ρ *reflectance*

τ *transmittance*

φ *solar azimuth*

ψ *surface azimuth angle*

ϖ *solid angle*

CHAPTER 1

INTRODUCTION

1.1 Background

Natural light has always played a dominant role in buildings, both to reveal the architecture of the building and to create a pleasant atmosphere, as well as to provide the occupants with visual comfort and functional illumination. The optimal use of daylight was, at the time of cheap energy, often seen as a superfluous design constraint. Illuminance deficiencies in the building were corrected with artificial lighting. The oil crisis and subsequent increase in energy prices, and now the even greater awareness of the impact of energy production on the global environment, has given an impetus to energy-conscious design.

With the growing interest in energy-conscious design in general and solar architecture in particular, the importance attached to energy use for artificial lighting in the non-domestic building sector has grown as well. It is estimated that about half the energy used in non-domestic buildings goes to artificial lighting. Waste heat from luminaires in winter may contribute to heating, but in summer energy is often wasted getting rid of surplus heat from luminaires by means of air-conditioning systems.

Moreover, the growing realisation that (i) the energy involved in the provision of artificial lighting contributes significantly to global environmental pollution and (ii) the deprivation of daylight may have detrimental psychological and physiological effects on the occupants of the building, have all given recently cause for concern. Daylighting has become, next to passive solar heating and passive cooling, a major topic in energy-conscious design.

The utilisation of daylight in buildings may have some disadvantages: glare, high contrast, variability, difficulty of control and excessive illuminances are some of them. All these problems have been addressed during the last twenty years. The revolution in daylight use in buildings has led to a huge number of inventions and products. These products include innovative daylight components and shading devices, as well as lighting control systems.

The main problem has always been the optimization of these systems. The building space, use and characteristics may be completely different from case to case, thus, different approaches have to be followed in daylighting design and in the utilization of daylighting systems.

1.2 Motivation

In recent years, there have been a large number of companies that have produced innovative daylighting components and shading devices. The old-fashioned simple double-glazed window is hardly ever found in new commercial buildings and modern offices. Instead, the systems used nowadays are quite complex optically in their majority. As a result, only few of them have been studied in detail in order to examine their optical characteristics and their transmission/reflection/absorption properties and, based on these, to evaluate the efficiency of such complex systems in a particular space. The fact that many of these products can be expensive leads to a need for detailed studies about their efficiency.

The development of several computer simulation programs for lighting and daylighting (Radiance, Superlite, Lumen-Micro, etc.) has reduced the problem. However, with the increasing production of these systems none of the existing software can simulate all of them. The horizontal venetian blinds are a good example of such a system that has been studied in the past, but the huge variety of products in this area requires a different study for each system in order to optimize its design and choose the one with the best daylighting efficiency.

1.3 Objectives

The main objectives of this thesis are the following:

1. To study the optical -transmission- properties of an advanced window system with integrated highly reflective motorized venetian blinds between the two panes, a system with the complex combined optical characteristics of a window and a shading device together and to generate solar radiation and daylight -visible- general transmittance equations for the whole window based on full-scale measurements in an outdoor test-room.
2. To develop an analytical detailed methodology for simulating the luminous flux and daylight transfer processes in a closed space and calculate the illuminance level on any point in a room -mainly on the work plane- due to daylight.
3. To determine the daylighting efficiency of this advanced window system in an office space.

4. To develop a control strategy that combines the use of natural daylight using this system and also the selective use of artificial lighting -dimming- in order to estimate the possible energy savings for an office space with such a window.

1.4 Thesis overview

Chapter 2 overviews the related literature. Different methodologies for calculating illuminance level in a space are presented. Recent innovative daylighting components are described along with modern shading devices and other systems for the daylight control in buildings and energy efficiency involving these systems is discussed. Emphasis is placed on motorized venetian blinds. Finally, the concept of dynamic control is introduced, combined with the use of predictive control algorithms for energy-efficient buildings.

In chapter 3 the advanced window system considered in this work is described and the experimental procedure is presented. After an analysis of the parameters involved in the transmission process, the general daylight (visible) transmittance equations and the solar radiation transmittance equations are determined for all possible cases and the results are discussed in detail.

Chapter 4 contains a numerical simulation of a typical office space with such a window system on a near south-facing façade. The illuminance level on the work plane is found for all working hours in the year using detailed analytical methods (solar geometry, form factors and configuration factors). Then, a comparison with experimental measurements is performed. Finally, a control algorithm is developed for the simultaneous control of the shading device and dimming of the electric lights. The daylighting efficiency of the advanced window is discussed and the possible energy savings of this dynamic control strategy are estimated.

Chapter 5 presents the conclusions of this study and also recommendations for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Daylight assessment

The realisation of the importance of daylighting in buildings resulted in a large number of daylighting studies. These studies extend from theoretical calculations of sky luminance/illuminance and analytical ways of predicting illuminance level in a closed space to the invention of complex optical systems for the control of daylight/sunlight and development of dynamic control strategies for the simultaneous optimal performance of HVAC systems and innovative daylighting components or shading devices.

A designer needs to evaluate each daylighting opinion from a lighting point of view and an energy point of view. Both criteria are critical for the optimum performance of a building. The best performance could be determined if a daylighting study for a building could be made before its construction (Baker, 1993). There are several methods to predict and assess the daylighting performance of a building:

1. Scale models. These are mock-ups of the real building. Scale models allow a qualitative and quantitative performance evaluation of the daylight systems used with respect to visual performance only. The designer can evaluate the impact of shading upon the indoor light levels, and also the distribution of daylight inside building spaces, due to the use of innovative daylighting systems (Bauman, 1987). The daylight assessment can be performed either in outdoor conditions (real sky) or under an artificial sky (Michel, 1995).

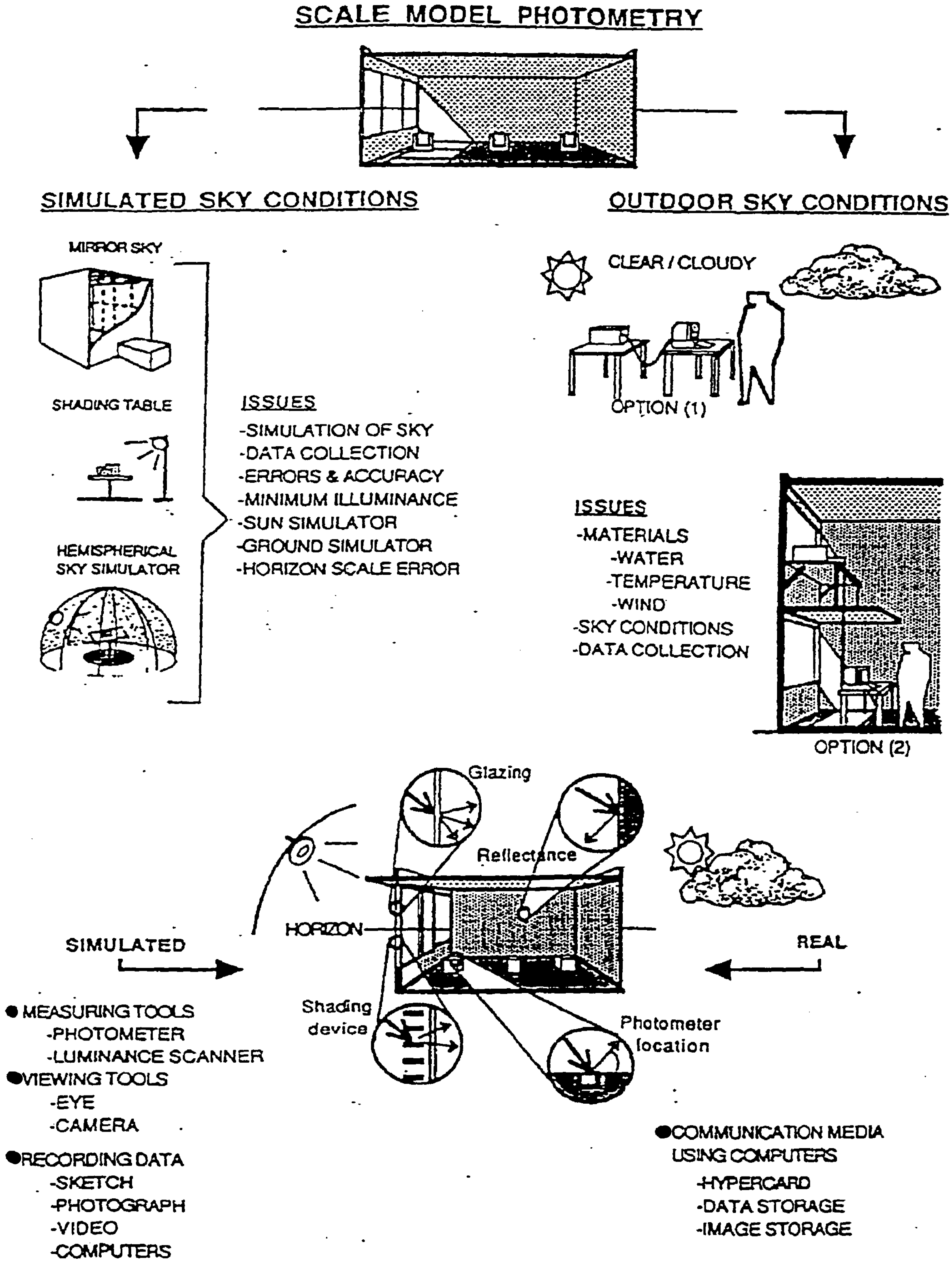


Fig. 2.1. Scale model photometry techniques and related issues (Baker, 1993).

2. Graphical tools. There are simple graphical tools allowing a rough assessment of various daylighting schemes. Common examples are the Waldram diagram method (Waldram, 1944), the Pilkington sky dot method (Pilkington 1969, Lynes 1969), the BRE overcast sky protractors (Longmore, 1967), etc.
3. Computer tools. The results of software tools can be linked with overall energy performance evaluation software. However, they differ on the approach and the detail they model the lighting behaviour of a space and therefore they all contain different types of errors.

2.2 Methodology for daylighting design

The qualitative and architectural aspects of daylighting are well studied in the past. The quantitative aspects of daylighting will be presented next, specifically towards providing the designer with sufficient information so that the average work plane illuminance and illuminances at several key points on the work plane in a space may be estimated.

The calculation procedures have four major components:

- First, the illuminances on the window and on the ground due to the sun and the sky and the reflected light from the ground have to be determined. Generally, two sky types are used: CIE overcast (Moon & Spencer, 1942) and CIE clear (Kittler, 1965). Recently, many different models have been developed for these sky conditions (Hooper, 1987, Harrison & Coombes, 1988) as well as for partly cloudy sky based on the possibility of sunshine (Littlefair, 1992) or the nebulosity index and even complicated combined models have been created (Perez, 1993). Many of these models seem to give accurate results and have been adopted by CIE.

- Using these data, the designer can predict the external illuminance, horizontal, vertical or sloped, on the fenestration (window, skylight, etc.). This requires inclusion of not only direct radiation from the sun and the sky but also reflected radiation from the ground and adjacent buildings.
- The third component of the daylighting design process is to ascertain the visual transmission characteristics of the fenestration material. Generally, there are two types of transmittances to consider, namely direct transmittance of sunlight and diffuse transmittance of clear/overcast sky light.
- The final step is to process the luminous flux which enters the interior space. There are several ways to do that (geometrical, analytical, general, etc) depending on the detail desired and the sky conditions. General ways to calculate the average illuminance on the work plane which are suggested by IES (1984), like the Lumen method of skylighting (Kaufman, 1981) and the Lumen method of sidelighting (IES, 1978, Kaufman, 1981) are not very accurate, but they can provide the designer with a good estimation of the average illuminance on the work plane.

2.2.1 The Daylight factor method

Another more detailed procedure has been developed and is widely used in Europe based on the work of many researchers over the past 80 years (Waldram, 1950, Hopkinson, 1966, Bryan, 1981, Robbins, 1984). It is called the dayiight factor method (DF), or split flux method. The daylight factor can be expressed to estimate the amount of daylight in the interior of a building. It is expressed as the ratio of the illuminance at a point on a plane produced by the luminous flux received directly or indirectly at that point from a sky of a given luminance distribution to the illuminance on a horizontal plane produced by an unobstructed hemisphere of this same sky:

$$DF = (E_i\ E_e)\cdot 100\% \qquad (2.1)$$

where E_i is the interior illuminance and E_e is the exterior illuminance. In the above definition, direct sunlight is excluded. Thus the daylight factor method has been limited to the cases of the CIE overcast sky and uniform overcast sky. However, other developments made the method valid for the CIE clear sky also, but they are quite complicated (Bryan, 1981). The three ways in which daylight may reach a point on a horizontal plane within a room are shown in Fig. 2.2. The sky component (SC) is the portion of DF due to daylight received directly from the sky. The externally reflected component (ERC) is the portion of DF due to daylight received directly at that point from external reflecting surfaces. Finally, the internally reflected component (IRC) is that portion of the DF due to daylight that reaches the point from internal reflecting surfaces. The total daylight factor is the sum of these three components:

$$DF = SC - ERC - IRC \qquad (2.2)$$

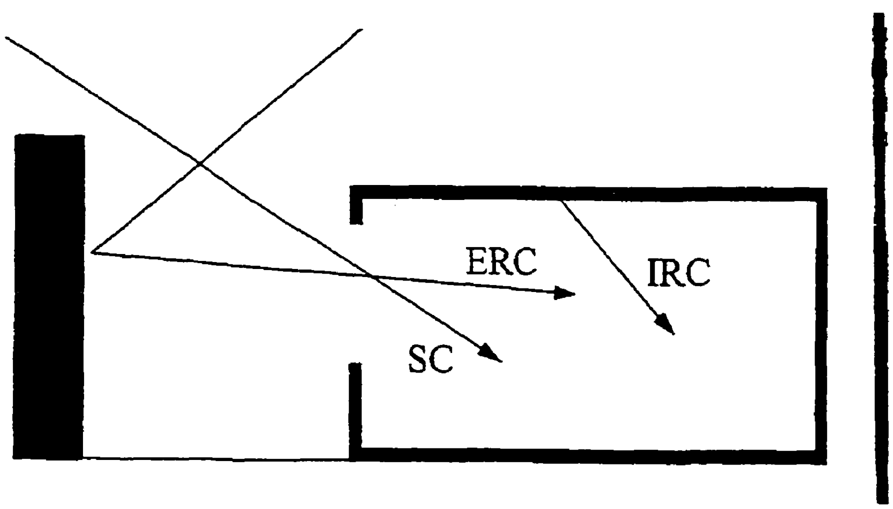


Fig. 2.2. The three components of the daylight factor.

2.2.2 The finite difference method

This method is product of the work of DiLaura (1979) and Siegel (1982), and it was presented as a complete method for the calculation of illuminance values by Goral (1984). The method is based on the principle of energy conservation and it allows the calculation of illuminance distribution on the surfaces of a closed space. The procedure can be summarized in the following diagram:

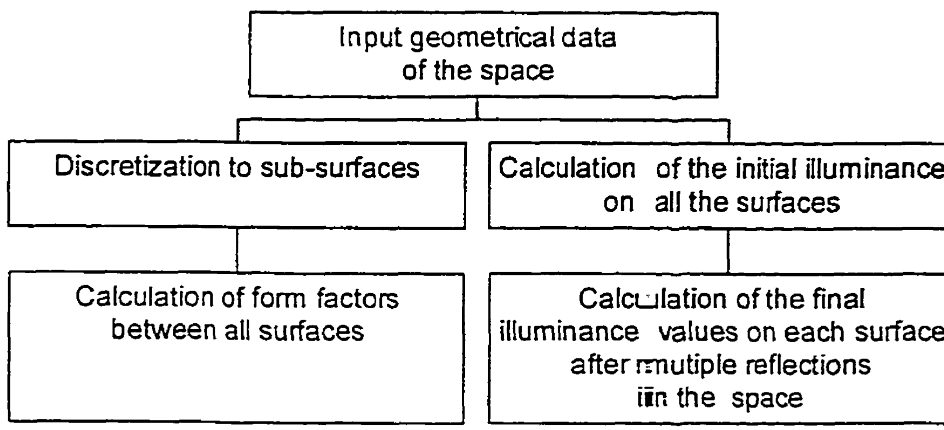


Fig. 2.3. The principle of the general finite difference method for the calculation of illuminance in a space.

It is obvious that the geometry of the space plays the most significant role in this method. Spaces with different geometries may have a completely different illuminance distribution under the same exterior daylight conditions. The separation of the surfaces in smaller surfaces increases the detail and the accuracy of results. However, the numerical complexity increases exponentially with the number of sub-surfaces. Usually, only the window surface has an initial illuminance value (except for the case that there is a skylight or other innovative daylighting components on the roof).

The form factors (or view factors) are analogous to the radiation shape factors in radiation heat transfer (Appendix B). They are strictly geometric quantities and they describe the exchange of luminous flux between two surfaces. The final illuminance on each surface after multiple reflections in the space can be found from the equation:

$$E_i = E_{oi} + \sum_j E_j \cdot F_{ij} \tag{2.3}$$

where E_{oi} is the initial illuminance (luminous exitance) of the surface, E_i is the final luminous exitance of the surface, E_j is the luminous exitance of all the other surfaces of the space and F_{ij} are the form factors. Using Eq. 2.3, the solution of the system of linear equations (Tsangrassoulis, 1997), can be solved either with matrix algebra (Murdoch, 1985), or with iterative algebraic methods, like the Jacobi or the Gauss-Seidel method. Generally, the finite difference radiosity method is the most accurate of all because it does not contain any empirical parameters and it is not based on the luminance of the sky. The only disadvantage of this method is that it cannot be employed in the case when the space consists of completely specular or mirror surfaces (Immel, 1986); the surfaces are considered diffuse or Lambertian (that is a very good approximation for most office spaces). A simplified version of this method is developed for the numerical simulation of an office space (chapter 4).

Recently, other methods for calculating the illuminance level in a space have been developed, e.g. ray-tracing techniques (Maxwell, 1986, Malley, 1988). The main disadvantage of these techniques is the numerical complexity and also that they are very time-consuming, although accurate.

2.3 Glare

Glare is defined by CIE as "the condition of vision in which there is a discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or extreme contrasts". Glare can be classified as direct and indirect or reflected. Direct glare is caused by the presence of a light source in the field of view. On the contrary, indirect glare involves two effects: reflected glare and veiling reflections. Reflected glare is caused by glossy surfaces reflecting the images of light sources into the eyes. Veiling reflections occur when small areas of the visual task reflect light from a window or a light fixture, reducing the contrast between the task and the immediate surroundings. This kind of reflection can occur when the angle of incidence of light on the horizontal working surface is within the observer's viewing zone.

Glare can be expressed as:

- Disability glare: it lessens the ability to see detail; it does not necessarily cause visual discomfort.
- Discomfort glare: it occurs when the presence of excessively bright sources in the field of view causes a state of discomfort, even with no significant reduction of the ability to see.

Several studies (Chauvel, 1980, Hopkinson, 1970) resulted in a combined general glare equation, known as the Cornell Index, which predicts the discomfort glare due to the sky seen from a window:

$$G = K \cdot \frac{L_s^{1.6} \cdot \Omega^{0.8}}{L_b + 0.07 \cdot \varpi^{0.5} \cdot L_s} \quad \textbf{(2.4)}$$

where:

K is a conversion constant

L_s is the luminance of the source

L_b is the luminance of the background

Ω is the solid angle subtended by the source, modified to take into account the position in the field of view

ϖ is the solid angle of the source with respect to the eye

When there are numerous light sources in the field of view, the above mentioned glare constants should be summed to determine the glare index (GI), according to the following expression:

$$GI = 10 \log \Sigma G \quad \textbf{(2.5)}$$

The most important functions of a window are to admit light into an interior and to provide a view outside. However, glare discomfort could arise from a direct view of the sky. To prevent this, excessive contrasts are reduced by controlling the direct light sources and by raising the luminance of the surrounding surfaces. There are three ways to do that: changing the window orientation, using glazings with varying transmission properties and other innovative daylighting components and/or using shading devices.

2.4 Recent development in glazings

The transmittance of clear glass and common double-glazed windows has been widely studied in the past (Riviero, 1958). The number of panes, the thickness, the extinction coefficient and the absorptance of the glass have an effect on the transmittance. Recently, more advanced glazings have replaced the traditional common double-glazed window. The low emissivity glazing (low-e) has a special coating on one surface, which reduces the longwave emissivity from about 0.9 to 0.1. These glazings can allow high solar gains into a room while minimizing heat losses through the glazing. The material and the thickness of the glazing affect the solar radiation transmittance of low-e glazings (Karlsson & Roos, 2000).

Variable transmission glasses are new developed glazings that allow the building envelope to be used dynamically, responding to outdoor climate and interior thermal needs. The principle of operation of electrochromic glazing (Cogan, 1986) is based on the change of the optical properties of certain laminated materials when subjected to an external electric field. The electrochromic coating is activated by a small electric voltage, generated by the building services or manually by the occupants. This voltage changes the tilt of the coating and therefore its transmittance. The life of electrochromic glazings is estimated around 4 years and this is a major drawback for their generalized use in buildings.

The thermochromic glazing (Lee, 1986) includes a thin tungsten trioxide or vanadium dioxide film. It passively switches between a heat transmitting and heat reflecting state, therefore it can reduce cooling loads and provide solar protection. Translucent glazings have low transmittance and they diffuse daylight; they are suitable for atria and skylights where direct visual communication with the exterior environment is not required. The photochromic glazing has a transmittance inversely proportional to the outdoor illuminance; when the illuminance is low, it acts as a normal glass, while in periods of high illuminance, it behaves as a body tinted glass (low transmittance and high absorptance). Other gasochromic and thermotropic glazings with a large dynamic range in total solar energy transmittance have also been developed and studied (Wilson, 2000).

2.5 Innovative daylighting components

The innovative daylighting components are advanced design features and components which are used to replace or complement window openings with respect to daylighting. They work by redirecting or diffusing sunlight or skylight into a space. These systems aim to increase daylight levels to the rear of deep rooms, improve the daylight uniformity within a space, control direct sunlight so that it can be an effective working illuminant and at the same time reduce glare and discomfort for the occupants (Littlefair, 2000). Apart from these, they can contribute to the reduction of energy consumption due to electric lighting and reduction in the cooling load.

Atria and skylights can be considered such components and they have been used for many years. More recently, other advanced systems have been (and are being) developed. A light-redirecting double-glazing system (Beck, 1999) consists of stacked acrylic blades section between the two panes of a window. The blades have a starting leading section, inclined 40° from the horizontal. The middle section is curved, in order to redirect most of the incident light at the interface. The end section of the blades is straight and longer, in order to redirect the light in the desired pattern. This system achieves a significant redistribution of ambient sunlight within a room, reflecting the light towards the ceiling, where it is diffused onto the working area, while at the same time glare is reduced significantly but not eliminated.

Prisms and diffusing glazings can be used in vertical windows as shading devices and/or as daylight guiding devices. They can reflect the direct sunlight, diffuse it or redirect it towards the ceiling. Lorenz (1998) has studied a glazing with a prismatic bar consisting of transparent material with a triangular cross-section. It rejects direct solar radiation during the summer period and transmits it during the rest of the year. It is based on the seasonal change in solar incidence angle (Appendix A) and on the capability of glass prisms to refract/ reflect/transmit solar radiation depending on the relevant incident angle.

A similar system (Lorenz, 2001) consists of two prismatic panes. The prismatic ribs of the panes are inclined by a certain angle to the horizontal, facing each other and positioned such that a small gap remains between them. The lower faces are coated with a specularly reflective layer, while the upper faces are covered with a diffusely reflecting layer. It can be applied to a wide range of window orientations and provides protection against direct solar radiation and glare in the summer, energy-saving properties, and good illumination of deep rooms and allows a good viewing field to the outside.

Sun ducts are devices that can bring light and ventilate interiors which are dark and damp (Coch, 2000). They consist of a capturing head, and a duct (light-pipe). They transport daylight from the roof of a building to spaces even 7m below. A dome with a reflector leads the sunlight into a highly reflective tube, which guides the light down to the space. On the bottom of the tube there is a diffuser that distributes the sunlight into the space. The transmittance of such a system depends on its dimensions and physical properties, but the average overall transmittance is about 50% (Argiriou, 1997).

Anidolic zenithal openings (Courret, 1994) are similar systems. The input and output beams are controlled by specular reflectors. They are based on non-imaging optics and consist of a parabolic concentrator above a parabolic deconcentrator, in order to guide daylight towards the bottom. They improve the illuminance distribution of a space significantly and provide complete protection from glare.

A holographic optical film is another system for redirecting light into a space. By the physical effect of diffraction, different forms of light manipulation are possible (Muller, 1994). They can also be used on the external surface of vertical windows in order to guide the zenith light indoors. Moreover, they can filter certain wavelengths of the solar spectrum and therefore the infrared part can be directed towards a part of an inner glass layer to reduce the heat gains of a space (Argiriou, 1997). Holographic optical elements can also be used to concentrate direct solar radiation on photovoltaic cells placed on transparent shading devices. In this way, only the diffuse daylight is transmitted into the space, while the sunlight generate electricity with an increased efficiency of about 40% per cell area (Muller & Capelle, 2000).

This attractive idea of multifunctional solar facades of buildings has just come in during the last few years. Systems that simultaneously produce heat and electricity, and at the same time they provide shading and daylight to the interior are highly appreciated (Steemers, 1994). The optimization problem is complex, but recent studies are optimistic (Vartiainen, 2000).

2.6 Shading devices

The requirement of maximizing natural light in building spaces is, during the summer, in conflict with the need to minimize solar gains in order to reduce energy consumption for air-conditioning. Except for the innovative daylighting components, shading devices or combined systems can help to minimize solar gains.

The amount of annual daylight incident on a window depends on the latitude of the place, the location, the ground reflectance, the orientation of the window and, of course, the sky conditions (assuming that daylight is not obstructed by adjacent buildings or vegetation). South-facing windows accept the greatest amount of daylight (and the higher solar gains). For an office space, it is necessary to avoid glare and high contrast, which cause discomfort to the occupants. Thus, shading provision should be considered as an integral part of fenestration system design, especially for south facades of buildings. Some examples of shading devices are shown in Fig. 2.4. The variety of shading devices is high, but they fall into two main categories: fixed and movable.

Fixed shading devices include overhangs, louvers, vertical fins, awnings and light shelves, whereas movable shading devices are mainly retractable roller shades, shutters, venetian blinds and curtains. The fixed devices are usually employed in the building envelope to exclude solar radiation in the summer (reduction in cooling load) and to admit it in the winter (reduction of heating requirements, Athienitis & Santamouris, 1999). However, they also block a significant amount of diffuse daylight on clear days and they are not effective under overcast conditions.

On the other hand, moveable shading devices can be adjusted to changing solar incidence angles (Sceatzle, 1990). They can allow the maximum possible amount of daylight into the space without causing glare on clear days, while, at the same time, they can allow all the available daylight under overcast days. These devices can be either manually operated (curtains, shutters, roller shades) or motorized (horizontal louvers/ venetian blinds, retractable roller blinds). In modern offices, the need for efficient automation systems is greater than ever and the motorized shading devices are predominating.

The diurnal and seasonal changes in the sun's position and the sky conditions cause a large and complex variation in the daylight transmitted through a window system with an integrated shading device. Thus a detailed study of all the parameters involved in the transmission process and a balance between the accuracy of calculations and numerical complexity is required (Tsangrassoulis, 1996).

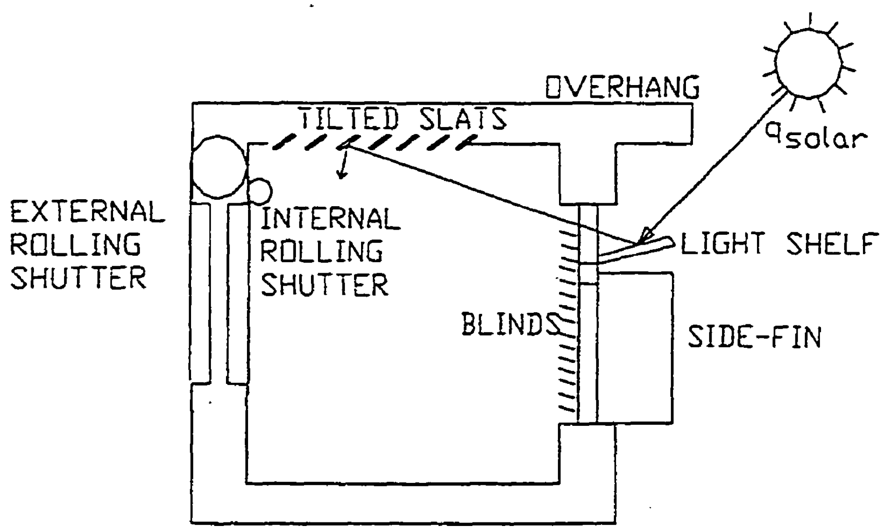


Fig. 2.4. Examples of shading devices (Athienitis & Santamouris, 1999).

2.6.1 Motorized venetian blinds

Motorized shading devices can be continuous (roller blinds), or discrete (venetian blinds). The optical and transmission properties of the continuous devices have been well studied and they are usually given by the manufacturer. In the case of the motorized venetian blinds, there has not been a detailed study combining all the parameters affecting the transmittance of the system. The shape, the colour, the dimensions and the tilt angle of the blinds are the most important factors for the determination of the transmission and reflection properties of such a system. For a common double-glazed window, the solar transmittance is only a function of the solar incidence angle i.e. the angle between the solar rays and a line normal to the surface. The venetian blind itself is an optically complex shading device, because it is non-homogeneous. It transmits, reflects, absorbs and diffuses daylight in a complicated way. Monte Carlo techniques can predict the direct and diffuse reflectance and transmittance of such a system for certain blind tilt angles in good approximation (Molina, 2000). The transmittance is a function of the solar altitude and the blind tilt angle; the solar azimuth has no effect on the transmittance since the blind is horizontal (Aleo, 1994).

Nevertheless, in the case of a complex window system with integrated venetian blinds between the two glazings, the transmittance of the system is a function of the solar incidence angle, the blind tilt angle and the sky conditions and the problem becomes quite complicated. For this kind of system, usually the transmittance is found for normal incidence and discretely changing blind tilt angle (Lee, 1998). In some other cases, the blind tilt angle is kept constant and the solar incidence angle changes (Tichelen, 2000), since the angular behaviour of solar radiation (and daylight) transmittance for different types of windows without shading devices has been studied a lot. The blinds reflect direct daylight towards the ceiling and this can be utilized using a ceiling reflector (Tichelen, 2000).

Generally, the motorized venetian blind is a multipurpose device: when the sun is present, it blocks the direct sunlight protecting the occupants from glare and reducing the cooling load in the summer (Rheault, Carle & Bilgen, 1987, Lee & Selkowitz, 1995); at the same time, it reflects the sunlight and sky light and transmits the reflected light from the ground towards the ceiling, improving the illuminance distribution at the deeper parts of a room. When there is only diffuse radiation, it can be adjusted to allow the maximum possible amount of daylight in the space and maximize the view field to the outside (Athienitis & Tzempelikos, 2001). During the winter, it can be completely closed at night, minimizing conduction heat losses through the window. Also, it can provide the occupants with the desired degree of privacy at any time. Moreover, it can be even used to serve multiple buildings (when on a south façade): while it provides all the above to an interior space, it reflects a great amount of sunlight (especially if it is highly reflective) which can be used to illuminate the north facades of neighbouring buildings (Pucar, 2000), just like south-oriented facades reflect daylight onto opposite facades under sunny conditions (Tsangrassoulis, 1999).

2.7 The concept of dynamic control for energy savings from daylighting

Developments in building envelope technologies with variable physical properties have created new energy-efficient opportunities to achieve significant savings in building energy, peak demand, and cost, with enhanced occupant satisfaction. Dynamic building envelope technologies include actively controlled venetian blinds and other motorized shading devices or advanced glazings, airflow windows and integrated photovoltaic systems. Coupled with electric lighting control systems, dynamic envelope and lighting systems can be actively controlled on a small time step to reduce the largest contributors to commercial building energy consumption: lighting, and cooling due to lighting and solar gains.

Furthermore, when combined with overall dynamic control of HVAC systems, it is possible to maintain thermal and visual comfort under continuously varying conditions. The conventional HVAC concept of dynamic control, introduced in the early 1970s with the development of lower cost microcomputers, has mainly two objectives:

- To anticipate upcoming weather or interior load conditions to minimize energy use
- To coordinate the operation of the HVAC components according to continuously varying conditions to maintain human comfort

For the first objective, the predictive control strategy is often designed to exploit the thermal mass of the building as a source of free cooling to dampen and shorten the building energy and peak demand requirements. Working with the previous day's temperature data, the optimal start-up time, setpoints and ramping rate to precool the thermal mass of the building, for example, can be determined through simulation and used online during the operation of the building.

The objectives of predictive control of dynamic envelope and lighting systems are different. Instead of using the thermal mass of the building to reduce peak loads, the operation of the dynamic envelope system can be coordinated with the daylighting control system to reduce envelope and light heat gains and to reduce the electric lighting power consumption on a short-term basis. The design and evaluation of predictive control algorithms is complicated by several factors: evaluating these algorithms using hourly building energy simulation programs is quite difficult; various time delays (building thermal capacitance, air transport through the HVAC system, sensors response) can affect the accuracy of building energy control and must be taken into account. Also, most building energy simulation models installed with the energy management control system are typically based on steady-state conditions. Discontinuities may lead to inaccurate control and unrealised energy savings.

Lee and Selkowitz (1995) compared the energy performance of simpler control strategies based on instantaneous, measured data with the performance of two hypothetical dynamic envelope and lighting systems (an electrochromic window and an automated venetian blind) in order to determine the incremental benefit of using more complex predictive control algorithms. The energy performance of simple control strategies is related to the solar-optical properties of the dynamic envelope and lighting system, the window dimensions and the window orientation. Energy and peak demand savings are highly dependent on the control strategy of the dynamic envelope and lighting system. Different control strategies are employed and the resulted reductions in electricity consumption are discussed. In the case of the automated venetian blind, integrated in a south-facing window, predictive control algorithms seem to result in greater energy savings than simple algorithms. However, this is not true for the case of the narrow-band electrochromic window and for north-facing windows.

Another study of thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale office (Lee, DiBartolomeo and Selkowitz, 1998) showed that there could be significant energy savings due to electric lighting and reduction in the cooling load. In this study, the automated venetian blind system was compared with a static venetian blind with the same dimmable electric lighting system. In all cases, the dynamic venetian blind performed much better than the static blind in the reduction of the cooling load. When there are no daylighting controls (static blind), the energy savings due to electrical lighting and cooling load reduction are also satisfying (22%-86% and 23%-33% respectively).

In the above studies, the direct sunlight is blocked at all times throughout the day, to prevent discomfort and glare. The occupants' response to such a system has been also studied (Vine, 1998). This survey included investigation of the occupants' estimation for the quality of work environment in an office building with a venetian blind, which could operate in three modes: fully automatic, auto/user control and manual. Although most of the examined occupants felt the overall lighting to be comfortable with the automatic mode, a bigger percentage felt that the conditions are more comfortable with the manual mode. However, in this case, more of the dissatisfied people complained about glare and high contrast. It is known that visual comfort and thermal comfort require subjective evaluation. Each person has a different attitude against different patterns of illumination; some of the occupants felt comfortable only when they had the complete control of the luminous environment, even when the illuminance levels were higher than 700lx on the work plane. Some others felt uncomfortable due to the movement of the blinds or the noise of the motor, especially under unstable daylighting conditions (partly cloudy days). The study suggests that a good approach would be the auto/user control mode, where the occupant can manually control the system whenever he feels uncomfortable;

nevertheless, in the case when a large number of occupants work in the same environment, this can lead to disagreements.

Other studies (Scheatzle, 1990) allege that human control of motorized shading devices is not reliable and causes a constant disruption to the occupants; a microprocessor shall automatically operate the blinds as an occupant would if he/she were to constantly monitor interior and exterior conditions. But in this way, psychological and physiological factors affecting human comfort are ignored.

In all of the above studies of windows with motorized venetian blinds, none has developed a general formula for calculating the visible transmittance and solar radiation transmittance, independently of location, orientation of the window and local time. Therefore, the need for creating such equations for an advanced window system with motorized venetian blinds is obvious: when the transmittance is known, the illuminance on a space with such a window may be calculated, and the control of the shading device and electric lighting system becomes easier; in the case when the building has many floors, a few outside sensors (even one on each façade) are enough for the accurate measurement of the exterior solar radiation incident on the whole building.

The transmittance of the window and the shading device is discussed in the following chapter. Using these equations, a simulation of an office space with this type of window can be performed (chapter 4), to estimate the daylighting efficiency of this system and estimate the possible energy savings due to electric lighting.

CHAPTER 3

EXPERIMENTAL MEASUREMENTS AND RESULTS

3.1 The experimental test room

The experimental measurements took place in an outdoor test-room placed on the roof of the Concordia University BE building in Montreal (latitude 44°N, longitude 74°W). The dimensions of the test-room are 3m×2.5m×2.5m and the window system is integrated on the façade facing 10 degrees east of south (Fig. 3.1). A high-rise building of Concordia University is hiding a portion of the sky to the West. However, it does not cause direct solar shading to the window during the summer (when the sun is high). During the fall season, it shades the window for solar angles of incidence only between 10 and 15 degrees. In all the other directions, the window is relatively free from obstructions. The ground reflectance is approximately 20% (no snow present).

3.2 Description of the window system

The window system was provided by Unicel -division of Arcon- and the manufacturer's trade name is identified as "Vision Control window". It is a double-glazed window with a low-emissivity coating and highly reflective horizontal louvers integrated between the two panes (Fig. 3.2). The window dimensions are 1.08m×1.08 (window area: 1.166m^2). A primary seal made of polyisobutylene is used for its high resistance against ultraviolet rays and it is combined to a secondary seal made of polysulfide. A highly effective drying agent provides moisture-free air space between glass panes, which are 6mm thick. The 50.8mm dehydrated air space reduces noise considerably. The louvers are made of extruded aluminium, hollow-chambered profile with

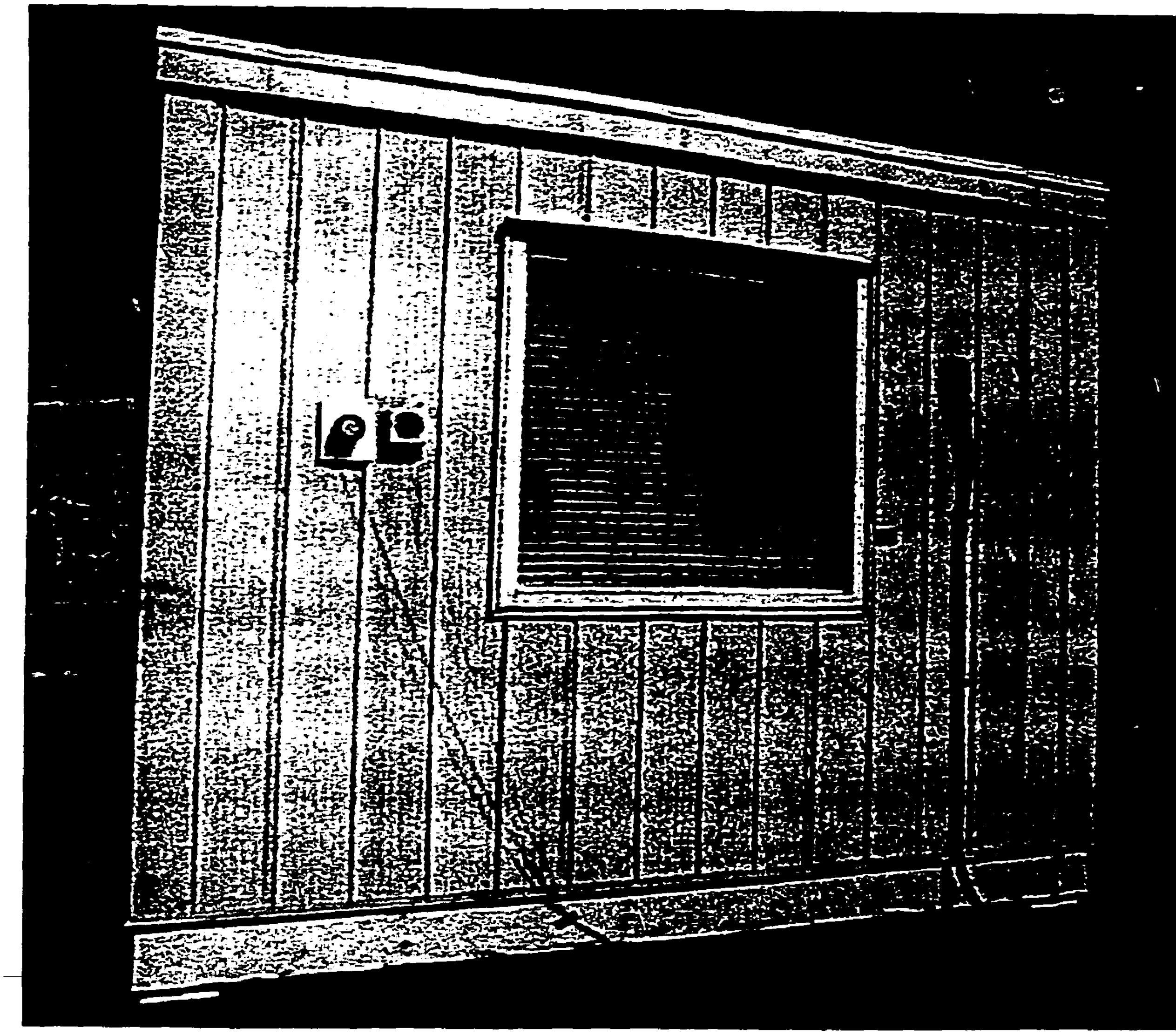


Fig. 3.1. An outside view of the test room. This is the façade facing 10 degrees east of true south with the Vision Control window.

overlap. They are 35mm wide and 6mm thick at the centre. They are secured at both ends with moulded pivots and they operate without cords or strings. It is designed to provide maximum rigidity and strength and maintain the parallel alignment of the blinds. The finish of the louvers and spacers is baked-enamelled DURACRON colour glossy white K-1285. Their operation can be motor-operated or optionally manual. They can rotate a full and continuous cycle (180°) in both directions by a motor (Fig. 3.3). Panels are mechanically ganged to enable one motor to operate multiple panels. Mechanical ganging is synchronous so that rotational orientation of louvers remains identical at all times. The motor operates at 10V DC and can rotate the blinds at the desired position when the appropriate signal is sent from a computer.

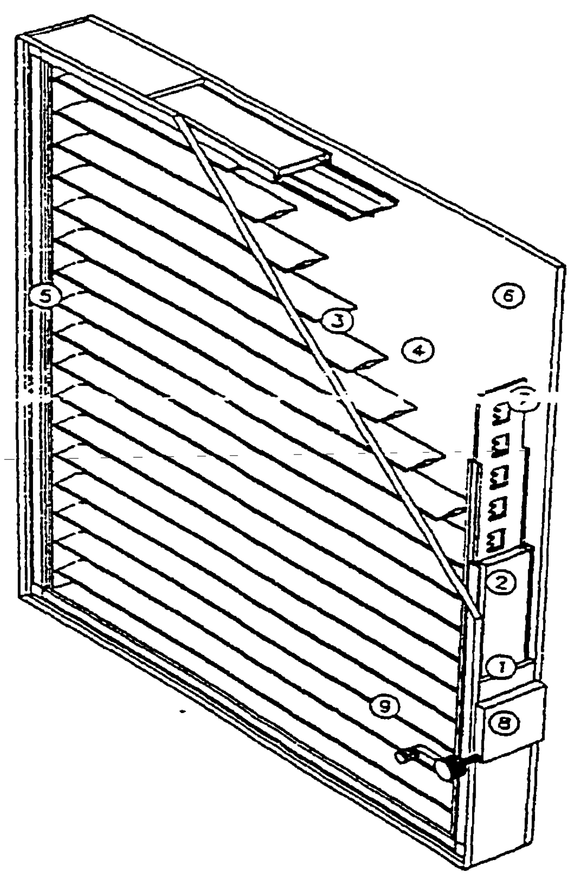


Fig. 3.2. Cross-section of the Vision Control window.

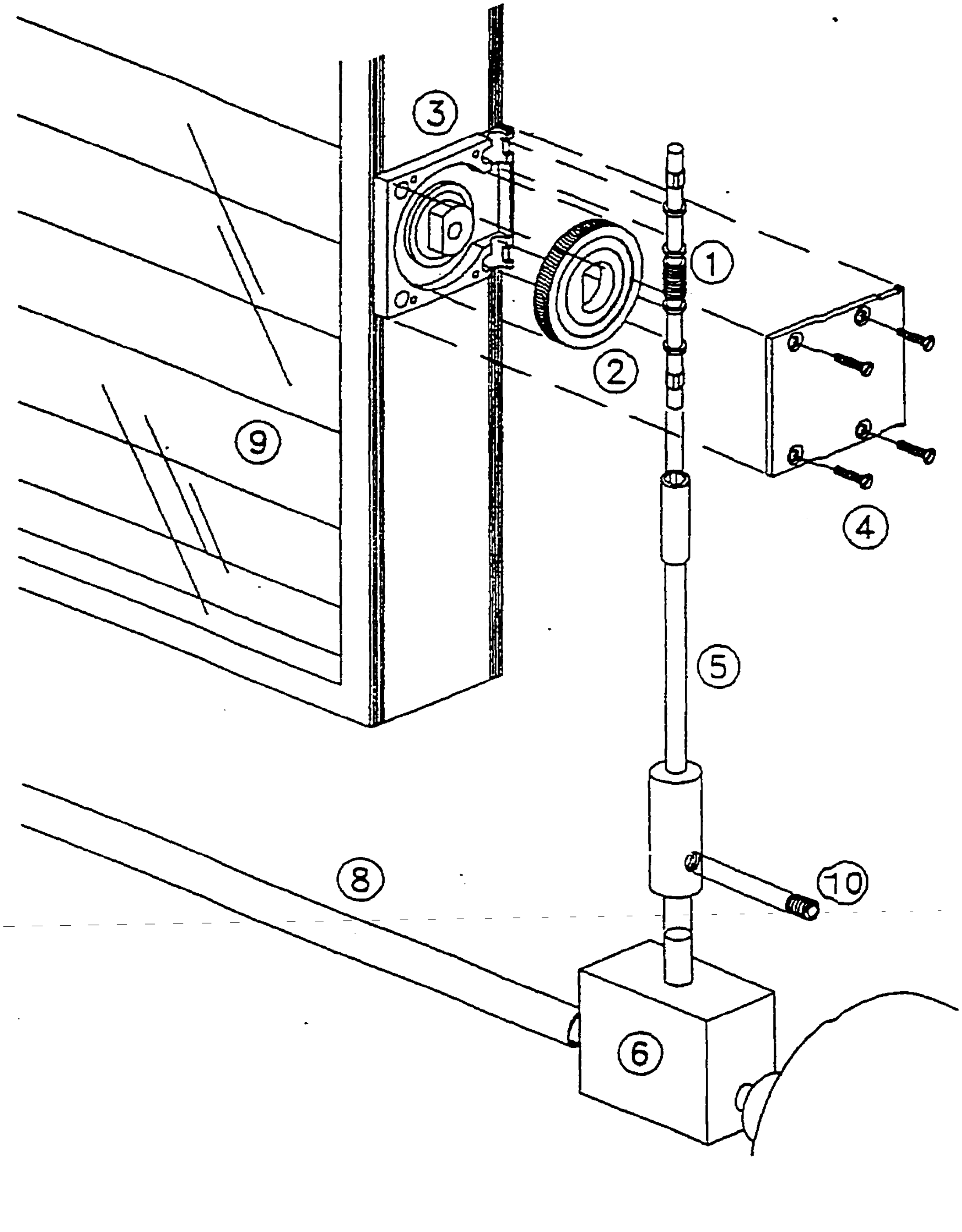


Fig. 3.3. Motorized mechanism of the Vision Control window.

3.3 Sensors and measurements

Several solar radiation and daylight sensors were used to measure solar radiation (W/m^2) and its visible portion (lx), respectively. All sensors were calibrated using an Eppley standard pyranometer and lux meter. Two sensors were mounted vertically on the wall just beside the outside surface window to measure the solar radiation and daylight incident on the window at all times and weather conditions (Fig. 3.1).

There is no standard procedure for measuring the transmittance of such non-homogeneous shading devices. Some methodologies seem to give accurate results (Aleo, Sciuto, Viadana, 1994). In this study two sensors (one for solar radiation and one for daylight) were mounted vertically at the centre of the inside surface of the window. A detailed study of the illuminance uniformity over the whole window area showed that, except for the parts near the sides of the window -where we have side optical effects- the daylight uniformity ratio (maximum/minimum value) was less than 110%, taking its maximum value at the centre of the window area (see Fig. 3.4). Another variation in the measured transmitted daylight is due to the relative position of the blinds and the sensor, which depends on the dimensions and also the shape of the sensor and the blinds. If the sensor is too small, its readings will contain significant error, because much of the transmitted daylight will be transmitted without being measured. If the sensor is too big, it hides a portion of the window to the interior space and this may reduce the illuminance level in the room. Measurements showed that for the selected sensors (circular, 0.04m diameter) this variation is negligible (the illuminance is almost constant with the distance between two successive horizontal blinds).

Another movable daylight sensor was installed in the room at a height 0.8m from the floor, to measure the illuminance level at different locations on the work plane, which is assumed to be approximately at that height in office spaces). The solar radiation sensors together with many thermocouples and other temperature sensors were installed for thermal control studies, which are not included in this study. An inside view of the test room with some of the sensors is shown in Fig. 3.5.

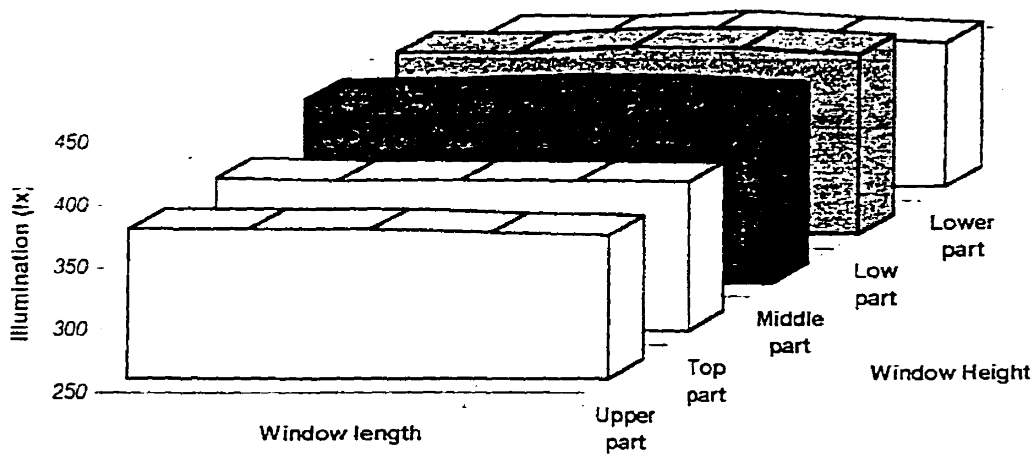


Fig. 3.4. Illuminance distribution over the window surface area.

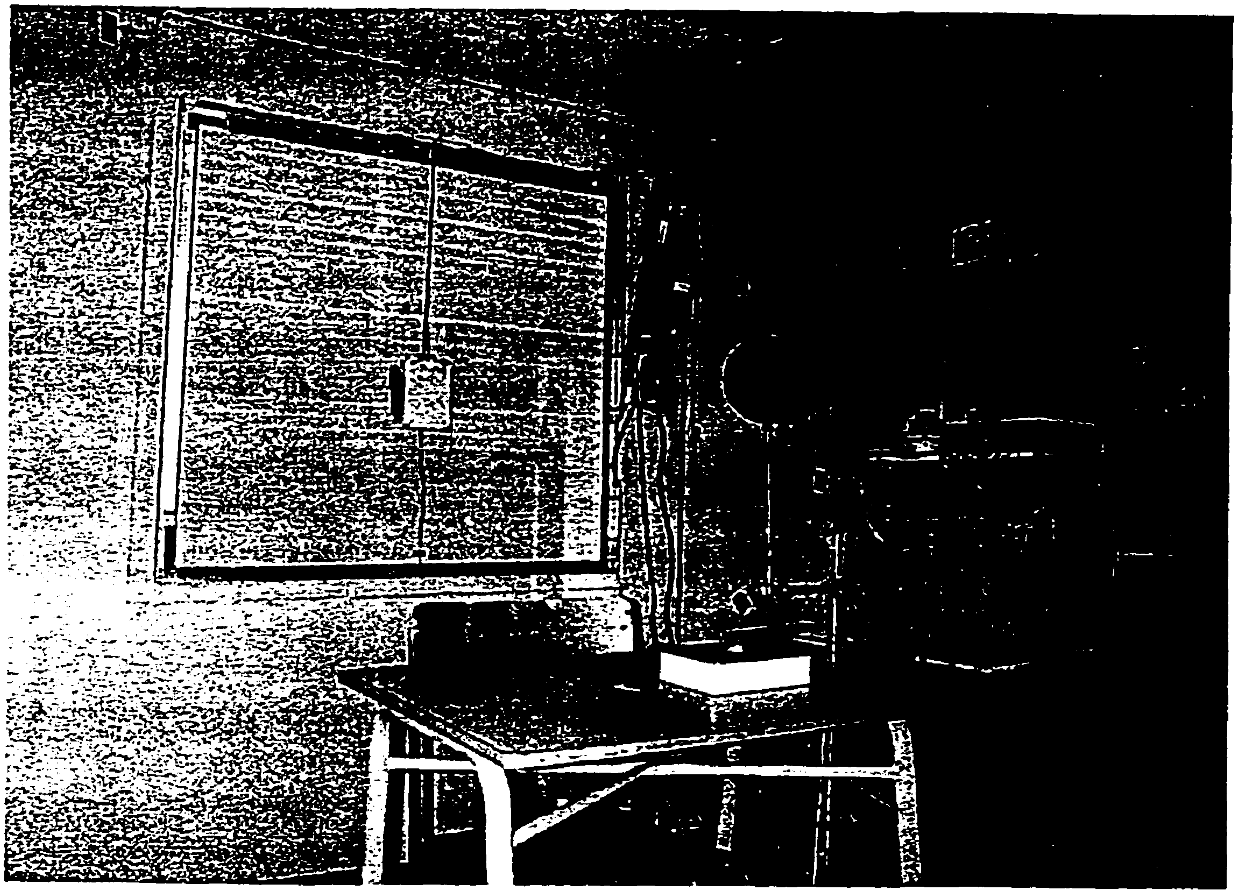


Fig. 3.5. Inside view of the test-room with the sensors, the window, the motor and the data acquisition system.

3.4 Data acquisition system

Data were collected for a period of five months, from July 2000 to November 2000. The data acquisition system used was DaqView 7.0, with 16 available connection channels on each of the 3 data acquisition cards. The interface used was a specially developed Visual C++ acquisition and control program interface. This interface was designed to offer the user more options in the control of the blinds and other heating systems connected to the data acquisition system (Fig. 3.6). It displays the readings of all the installed sensors. Data were usually sampled every 6 seconds and averaged every 6 minutes, but this can be changed depending on the desired detail for the analysis of the data. The blinds rotate and reach the desired position depending on the output signal, which is transmitted to the motor when one of the two direction buttons on the interface is pressed and the time interval of the rotation is specified. The measurements were detailed and included the collection of data for all blind tilt angles (0°-180°), for all times of the day and for different sky conditions, in order to achieve a general and accurate characterization of the transmittance properties of the window system, which is described in detail in the following section.

3.5 Transmittance of the window

The diurnal and seasonal changes in the sun's position and the sky conditions cause a large and complex variation in the daylight transmitted through a window system with an integrated shading device. Thus a detailed study of all the parameters involved in the transmission process and a balance between the accuracy of calculations and numerical complexity is required.

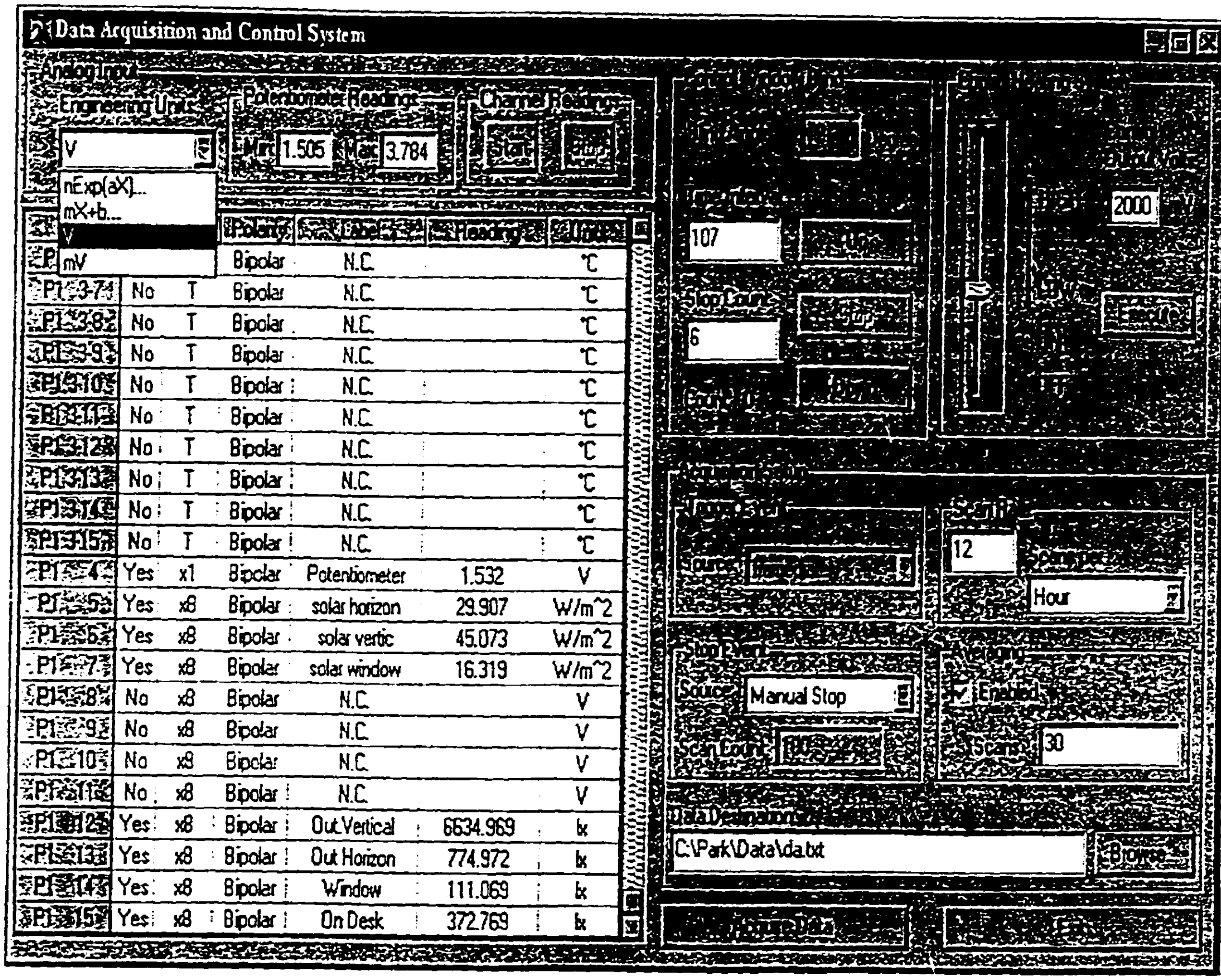


Fig. 3.6. The data acquisition and control system interface.

3.5.1 Parameters affecting the transmittance of the window

One of the objectives of this project was to examine whether this type of window provides a space with adequate daylight to ensure visual comfort and at the same time blocks and controls direct sunlight on clear days, by reflecting it towards the ceiling. In order to estimate these and to provide a useful and practical tool for theoretical simulations, a general transmittance equation for the window has to be determined, since such an equation is not provided by any software or standard.

The transmittance of a common double-glazed window is only a function of the solar incidence angle, θ (the angle between the solar rays and a line normal to the surface). The venetian blind itself is an optically complex shading device, because it is non-homogeneous. It transmits, reflects, absorbs and diffuses daylight in a complicated way. The transmittance of the venetian blind itself (without the window) is a function of the solar altitude, α, the blind tilt angle, β, and the sky conditions. The solar azimuth has no effect on the transmittance since the blind is horizontal (in the case of vertical fins, the transmittance is affected by the solar azimuth and not the solar altitude). The sky conditions is a parameter which affects the transmittance of the blind because light is reflected, scattered and transmitted in different ways depending on whether light is diffuse or direct. This is illustrated in much detail in the graphs of the following sections. In the case of such an advanced window, the situation becomes quite complicated. For this kind of systems, usually the transmittance is found for normal incidence and discretely changing blind tilt angle.

Taking into account the above, it is obvious that there is a need to produce general and accurate transmittance equations for such a window system with venetian blinds integrated between the two panes. The transmittance will be a multivariate function of three variables: the solar angle of incidence, θ, the blind tilt angle, β, and the sky conditions. The next sections describe the methodology followed to extract these equations for such a complex window system.

3.5.2 The sky conditions

The sky conditions can never be completely stable; they are continuously changing with time. On overcast days, there is quite a large variability in the sky conditions. The clouds are constantly moving, especially if there are strong winds in the upper atmosphere. Also, depending on the thermodynamic conditions of the troposphere, their size, shape, colour, density and content can change significantly. These variations affect greatly the way daylight is transmitted and scattered through the atmosphere. On clear days, things are better and the only problem that may affect the daylight scattering and transmission through the atmosphere is the presence of high relative humidity, which causes condensation of water vapour on possible dust/pollutant particles, mainly in the cities. Generally, this effect is negligible and when the sky is clear (nebulosity index <5%), the conditions are stable. When the sky conditions are variable (there are clouds and also clear parts in the sky), the situation is unpredictable and different patterns are made every minute in the sky, resulting to absolutely unstable and changing daylighting conditions on the ground.

For this study the transmittance values are extracted for sky conditions similar to: (i) the CIE overcast sky and (ii) the CIE clear sky. Because two days (clear or overcast) cannot be perfectly identical, measurements were taken for a large number of days falling into each of these categories and then statistical analysis of the collected data gave average values for the transmittance on a typical cloudy and a typical sunny day.

3.5.3 The blind tilt angle, β

The blinds can rotate in both directions. Starting from the downward position (blinds fully closed), the blind tilt angle β is measured anticlockwise, as shown with the arrow in Fig. 3.7. When the blinds are at the horizontal position, β is equal to 90 degrees. When the blinds block the sunlight (Fig. 3.7), β is greater than 90 degrees and finally when the blinds are fully closed at the upward position β is equal to 180 degrees.

The blind tilt angle can be changed degree-by-degree for the measurements using the control interface of Fig. 3.6, but in most cases measurements were taken every 15 degrees from 0° to 180°.

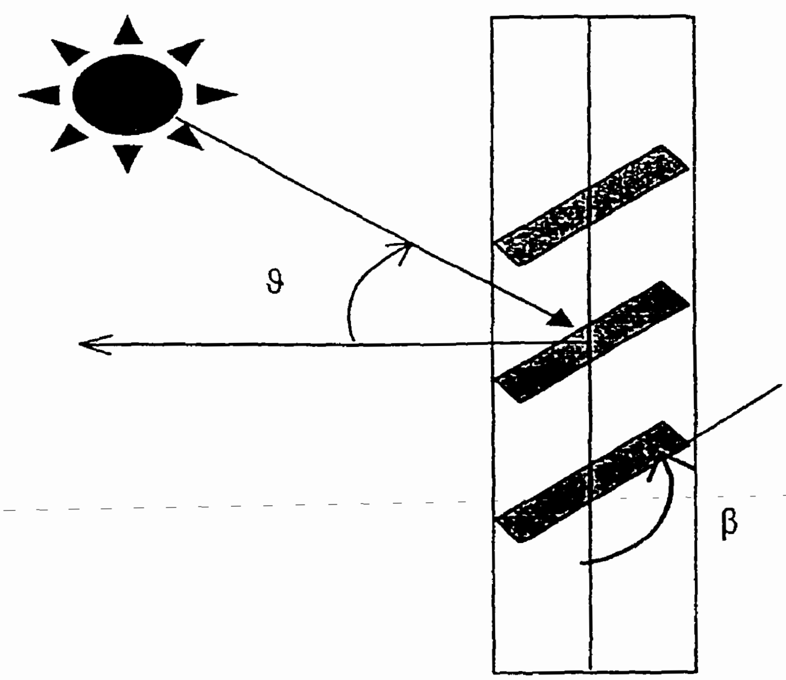


Fig. 3.7. The measurement of the blind tilt angle, β.

3.5.4 The angle of incidence, θ

The angle of incidence or solar incidence angle is the angle between the solar rays and a line normal to the surface (Fig. 3.8). It is given by:

$$\vartheta = cos^{-1}\left[cos(\alpha) \cdot cos\left|\varphi - \psi\right|\right] \qquad (3.1)$$

where α is the solar altitude, ϕ is the solar azimuth and ψ is the surface azimuth angle. The equations that give the above quantities as a function of solar time and day number in the year are in Appendix A.

While keeping constant the blind tilt angle, measurements may be performed for different angles of incidence. The reasons for selecting as variable the angle of incidence and not the time of the day are the following: first, the transmittance of the window depends on the relative position of the sun to the window surface (indicated by the incidence angle) and not the local time; the angle of incidence changes also with day number (except for time of the day); second, and most important, having the transmittance in a formula containing the incidence angle makes it possible to create a general transmittance equation, which can be employed for any time and day in the year, any orientation of the window and any location in the world.

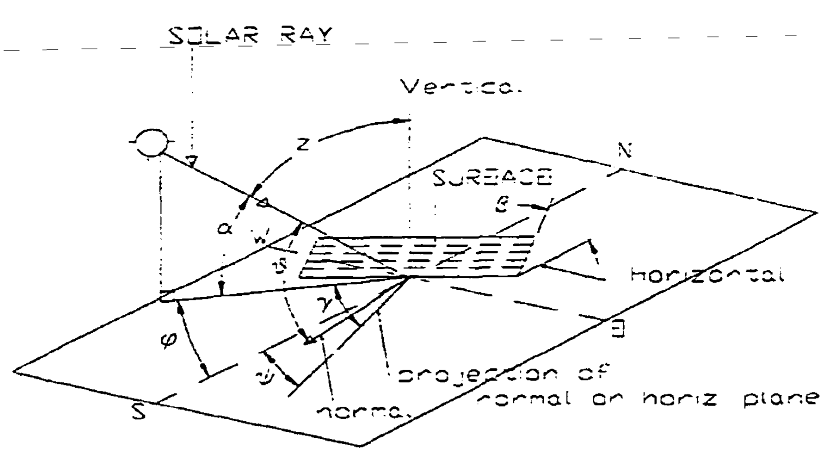


Fig. 3.8. Solar and surface angles involved in the calculation of the angle of incidence, θ.

3.5.5 Transmittance graphs and equations

The transmittance value for a certain blind tilt angle, angle of incidence and sky conditions is calculated by dividing the radiation measured on the inside surface of the window by that measured with the exterior sensors. Figures 3.9-3.12 show the visible transmittance (τ_v) as a function of blind tilt angle (β) and solar incidence angle (θ), for both overcast and clear days.

On overcast days, the angle β has a very strong effect on the daylight transmittance (Fig. 3.9). The curve reaches a maximum at about $\beta = 60°$ for all angles of incidence, and it is not symmetrical about that point. For this blind tilt angle, the maximum value is $\tau_v = 38.2\%$, for $\theta = 27°$. It is obvious that the solar incidence angle has a negligible effect on τ_v, compared to β, since the sun is not present (there is only diffuse daylight). This is clearly demonstrated by the lines of Fig. 3.10, which are almost horizontal for all blind tilt angles (within ± 3%-4% error). Thus, on overcast days, the maximum amount of daylight is transmitted for 60 degrees blind tilt angle at all times. These curves may be approximated by an equation independent of θ (only a function of β). Using multivariate fitting, the equation found is the following:

$$\tau_v^{diffuse}(\beta) = \frac{4.5 \cdot 10^{12} \cdot \beta^{-6}}{e^{\frac{335}{\beta}} - 1} \qquad (3.2)$$

where β is in degrees.

In the case of clear sky, the situation is quite different. The sun is present in the sky and the incidence angle has a stronger effect in the transmittance, compared with the overcast sky case (Fig. 3.12). The visible transmittance is higher for smaller incidence angles, but there is a relative minimum around $\theta = 45°$. For higher incidence angles the transmittance is constant for every blind tilt angle with very good approximation. Of course, the blind tilt angle plays again the most significant role in the determination of the transmittance value. The maximum transmittance value occurs for $\beta=75^\circ$-80° for all incidence angles, but the maximum value is measured for $\beta=78^\circ$ and $\theta=15^\circ$, and it is $\tau_v=55\%$, which is very high. It seems that the transmittance curve is almost symmetrical about $\beta=80$ degrees. In order to produce one single equation that describes the behaviour of the transmittance curves for all blind tilt angles and solar incidence angles, many multivariate regression techniques were employed, but the best fit was found using the following formula:

$$\tau_v^{clear}(\beta,\theta)=0.55\cdot e^{-\frac{(\beta-80)^2}{1900}}\cdot(-4.917\cdot10^{-7}\cdot\theta^4+0.000009\theta^3-0.00567\cdot\theta^2+0.13\cdot\theta-0.0437) \qquad (3.3)$$

The above equation consists of two terms: the first one describes the effect of blind tilt angle, β, on the daylight transmittance: it is a normal distribution approximation with the maximum of the curve at $\beta=80$ degrees, as it is shown in Fig. 3.11. The second term describes the effect of θ on the transmittance; it is approximated by a 4th-degree polynomial, fitting very well with the measured data. Although the curves in Fig. 3.12 are quite different for different blind tilt angles, the combination of this polynomial with the first term of the equation predicts the transmittance values for every β and θ with less than 10% error (errors occur only for $\beta \cdot 140^\circ$), which is inevitable for such a complex function.

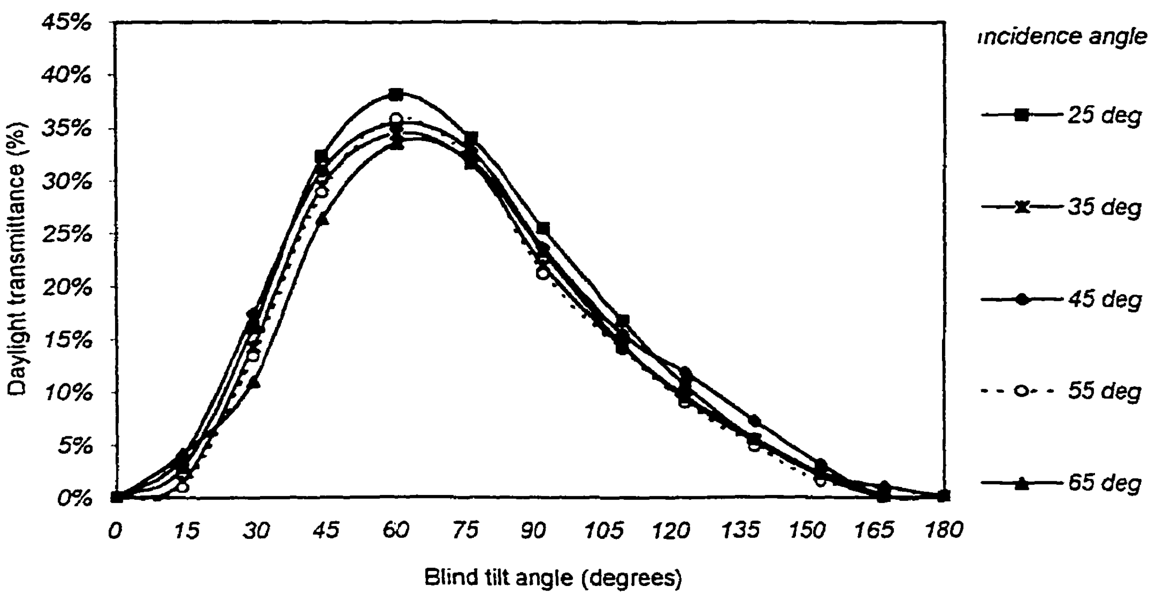


Fig. 3.9. Daylight transmittance as a function of the blind tilt angle for different incidence angles, overcast day.

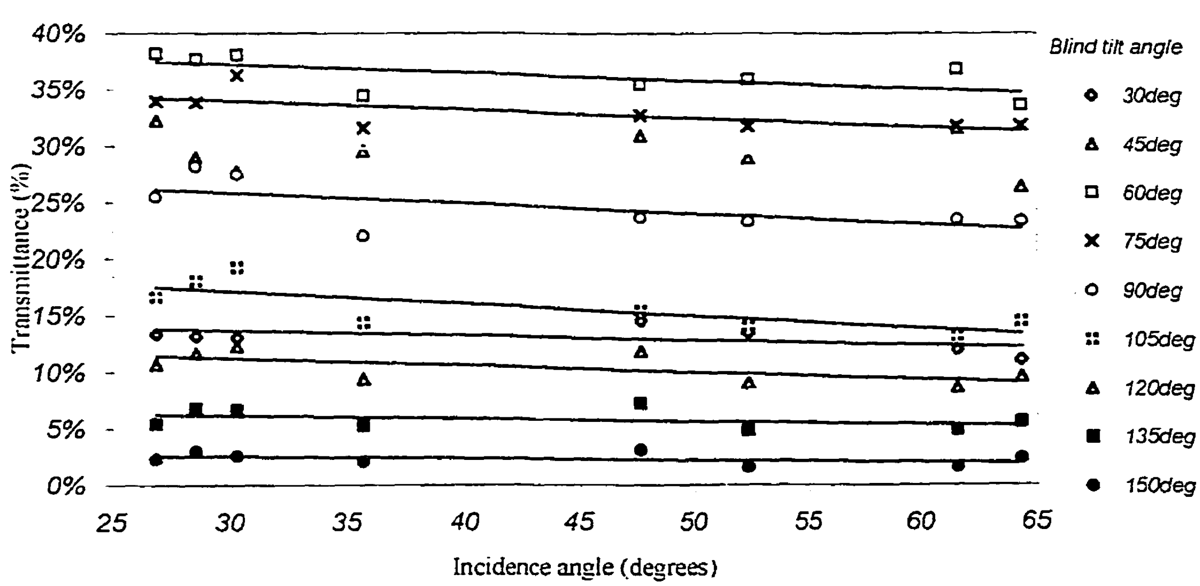


Fig. 3.10. Daylight transmittance as a function of solar incidence angle for different blind tilt angles, overcast day.

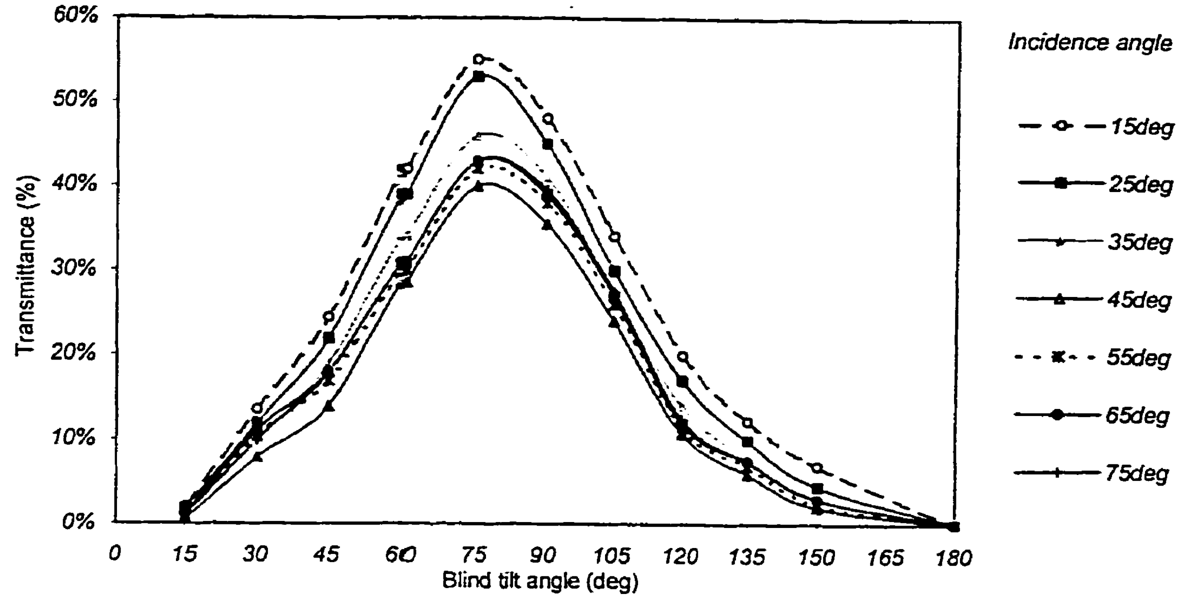


Fig. 3.11. Daylight transmittance as a function of blind tilt angle for different incident angles, clear day.

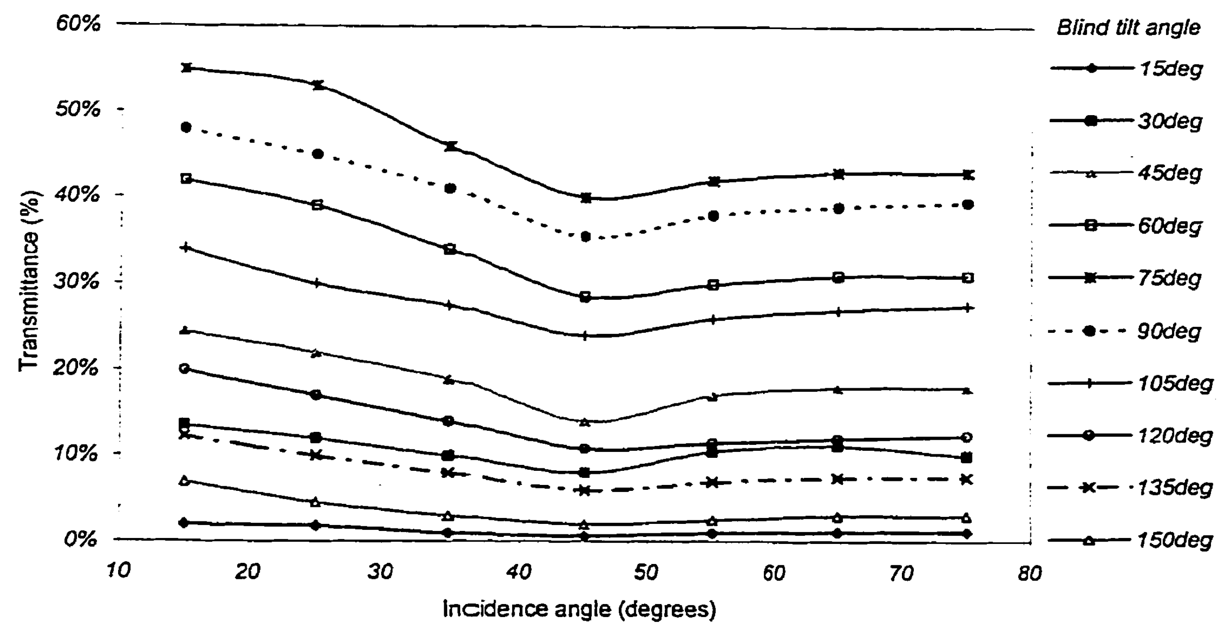


Fig. 3.12. Daylight transmittance as a function of solar incidence angle for different blind tilt angles, clear day.

Comparing the above graphs, the effect of the sky conditions on the daylight transmittance is obvious: during clear days (when there is plenty of daylight), the transmittance is significantly higher (about 20%). This is due to the spectral properties of the window.

The solar radiation transmittance, τ_s, was also determined in order to be used for thermal studies where solar gains have to be considered. In exactly the same way as for the daylight transmittance, the solar radiation transmittance was measured for different blind tilt angles, solar incidence angles and for both clear and overcast days. The equations are about the same as for the visible transmittance and the only difference is that, for overcast days, the transmittance is also a function of the angle of incidence (and not only of the blind tilt angle, as in the daylight transmittance). The solar radiation transmittance equations for overcast day and clear day respectively are the following:

$$\tau_s(\beta,\theta) = \frac{6.1605 \cdot 10^{12} \cdot \beta^{-6}}{e^{\frac{335}{\beta}} - 1} \cdot (0.0089 \cdot \theta + 0.771) \qquad (3.4)$$

and

$$\tau_s(\beta,\theta) = 0.475 \cdot e^{\frac{(\beta-77)^2}{1600}} \cdot (-4.081 \cdot 10^{-7} \cdot \theta^4 + 7.86 \cdot 10^{-5} \cdot \theta^3 - 0.005133 \cdot \theta^2 + 0.123 \cdot \theta + 0.00783) \qquad (3.5)$$

A significant difference with the corresponding daylight transmittance is that the solar radiation transmittance is higher under an overcast sky than for clear days (it reaches 65% for overcast day and 48% for clear day). This is due to the spectral properties of the window and the blinds. Although the shape of all curves is similar for both cases (solar radiation and visible radiation), solar radiation and visible radiation are transmitted in different ways through the window system. The following figures show the solar radiation transmittance for overcast and clear day respectively.

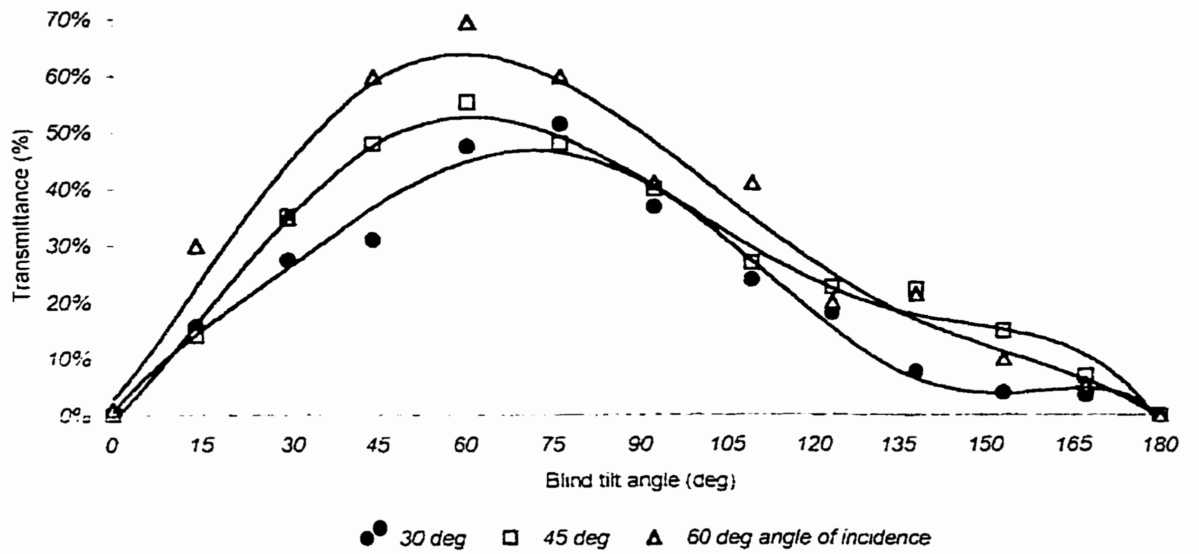


Fig. 3.13. Solar radiation transmittance as a function of blind tilt angle for different solar incidence angles, overcast day.

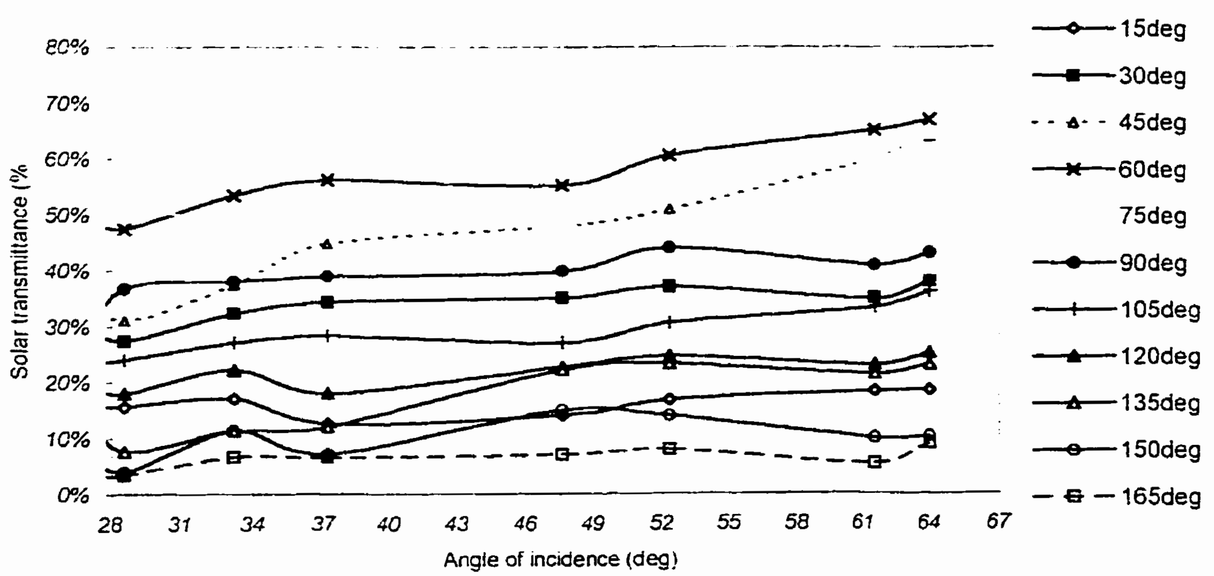


Fig. 3.14. Solar radiation transmittance as a function of angle of incidence for different blind tilt angles, overcast day.

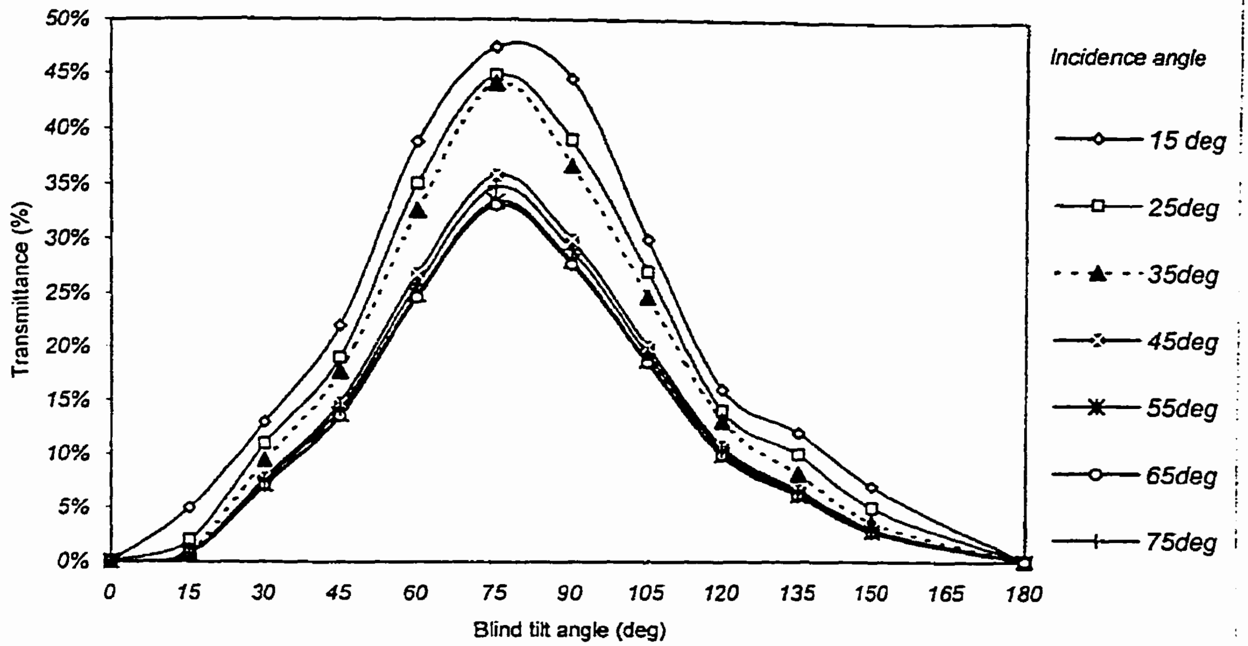


Fig. 3.15. Solar radiation transmittance as a function of blind tilt angle for different solar incidence angles, clear day.

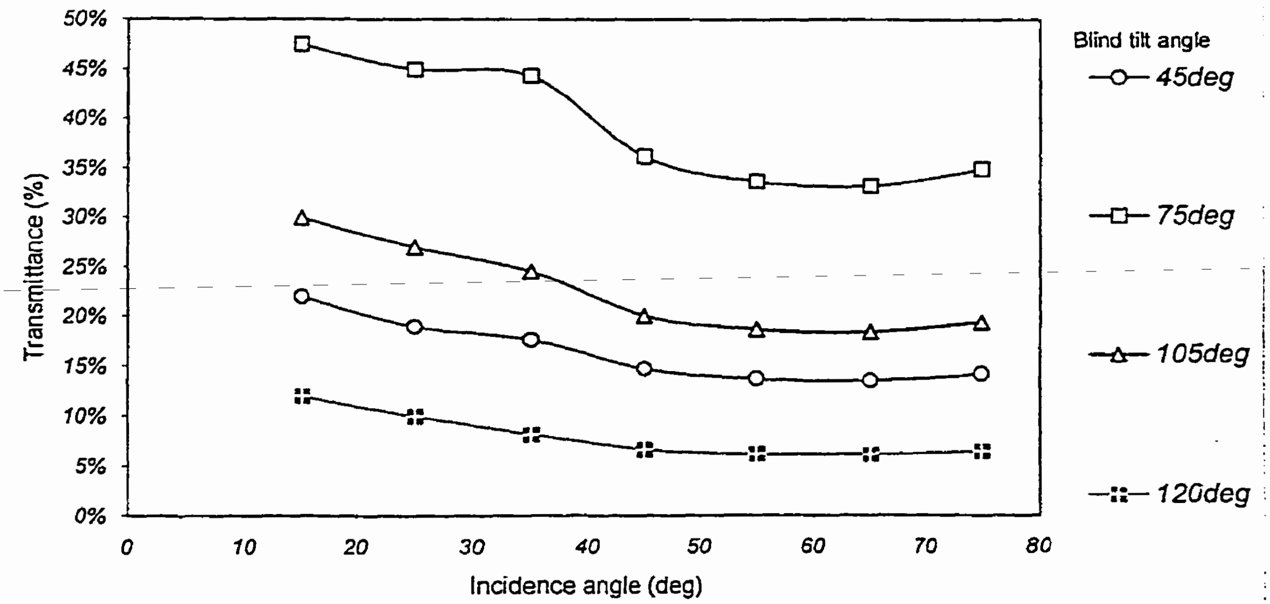


Fig. 3.16. Solar radiation transmittance as a function of angle of incidence for different blind tilt angles, clear day.

CHAPTER 4

SIMULATION OF THE WINDOW SYSTEM PERFORMANCE AND LIGHT DIMMING IN A TYPICAL OFFICE SPACE

4.1 Methodology

A simplified version of the finite difference method is developed for the numerical simulation of an office space with a Vision Control window. The simulation program calculates the optimum tilt angle of the blinds, in order to transmit the maximum possible amount of daylight without causing glare and at the same time allow the maximum possible view outside. The illuminance distribution due to daylight is determined on the work plane based on detailed radiosity analysis, including the computation of all necessary form and configuration factors. Then, the electrical light needed to achieve the required total illuminance level on the work plane is computed and dimming levels are established for all the electric lights in the office. Finally, the possible annual energy savings from simultaneous control of the blinds and dimming of the electrical lights are calculated (Fig. 4.1).

The program was developed in MathCAD 2000 Professional and it is presented in APPENDICES A-F. The shading device and electric lights dimming control algorithm may be implemented in an intelligent building automation system in conjunction with simultaneous control of HVAC systems.

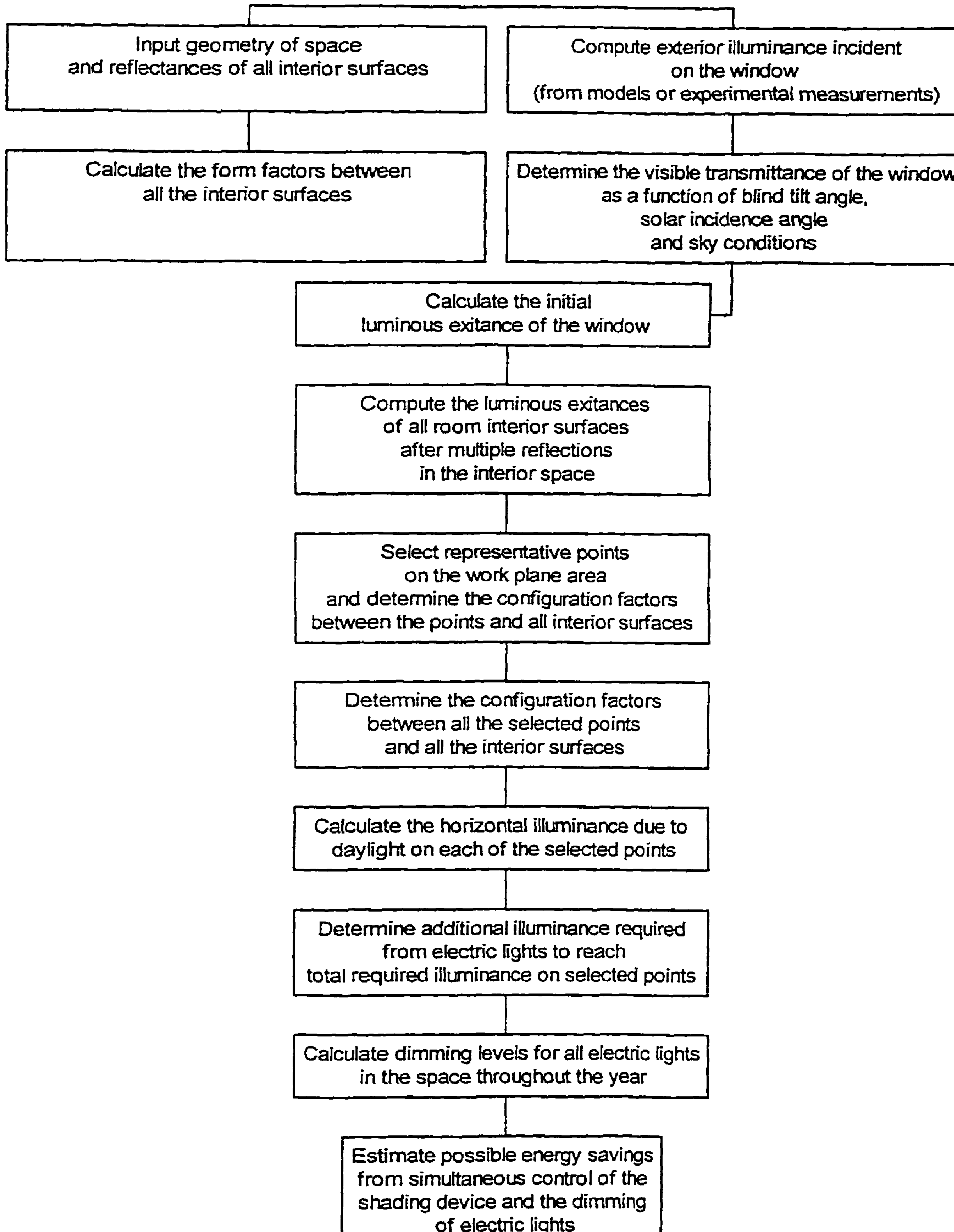


Fig. 4.1. Flowchart of methodology developed.

The input parameters to the program are: room dimensions and interior surfaces reflectances, window dimensions, position and orientation, location of the room, local time and ground reflectance. Here a 5×5×3m unfurnished office space is considered (Fig. 4.2) located in Montreal (44°N, 74°W), with a 2×4m Vision Control window on the façade facing 10° east of south, with no obstructions. The ground reflectance is assumed equal to 20% (no snow), the floor reflectance 30%, the ceiling reflectance 80% and the reflectance of all sidewalls 70%. The angle of incidence is first calculated as a function of t and n (APPENDIX A):

$$\vartheta(n,t) = \cos(a(n,t)) \cdot \cos(\varphi(n,t) - \psi) \qquad \textbf{(4.1)}$$

where a is the solar altitude, φ is the solar azimuth and ψ is the window surface azimuth (assumed equal to -10°, east is considered negative). The next step is to calculate the illuminance incident on the window and the daylight transmitted into the room. At this point sky conditions must be selected.

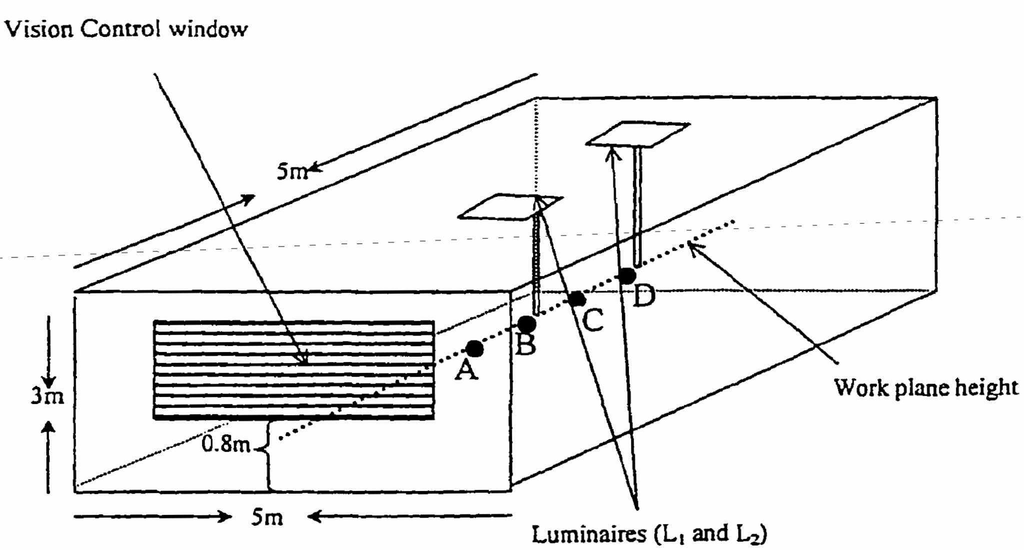


Fig. 4.2. The office space considered for the simulation.

4.2 CIE overcast sky

In this case there is only diffuse daylight incident on the window coming from the sky and the ground and glare is not much of concern. The maximum possible amount of daylight is transmitted in the room for β=60° (Fig. 3.9). In order to allow also a better view to the outside, the optimum blind tilt angle selected is: $\beta_{opt}^{diffuse} = 75°$. For this blind tilt angle, the visible transmittance is approximately: $\tau_v \approx 30\%$.

The daylight coming from the sky is equal to the horizontal illuminance multiplied by the view factor between the sky and the window, $F_{w\text{-}sky}$, which is assumed 0.5 (window "sees" half of the sky). The daylight reflected from the ground is equal to the horizontal illuminance multiplied by the ground reflectance (ρ_g) and the portion of that which is incident on the window is found by multiplying that by the view factor between the ground and the window $F_{w\text{-}gr}$, which is again assumed equal to 0.5 for the same reason. The daylight incident on the window will be the sum of these two terms. The horizontal illuminance under a CIE overcast sky at a certain day and time may be expressed as (Gillette & Kusuda, 1982):

$$E_h^{diffuse}(n,t) = 1000 \cdot (0.3 + 21 \cdot \sin(\alpha(n,t)) \tag{4.2}$$

Thus the daylight incident on the window on a overcast day (n), at time (t) will be:

$$E_w^{diffuse}(n,t) = E_h^{diffuse}(n,t) \cdot F_{w\text{-}sky} + E_h^{diffuse}(n,t) \cdot F_{w\text{-}gr} \cdot \rho_g = E_h^{diffuse}(n,t) \cdot F_{w\text{-}sky} \cdot (1 + \rho_g) \tag{4.3}$$

The daylight transmitted in the room is equal to:

$$E_{overcast}(n,t) = E_w^{diffuse}(n,t) \cdot \tau_v^{diffuse}(\beta_{opt}^{diffuse}) \tag{4.4}$$

4.3 CIE Clear sky

The daylight incident on the window on a clear day consists of three terms: direct sunlight, diffuse light from the sky and reflected light from the ground. The horizontal illuminance due to the sky may be calculated from (Kittler, 1981, Gillette and Pierpoint, 1982, Gillette, 1983):

$$E_{hsky}^{clear}(n,t) = 800+15500\cdot[\sin(a(n,t))]^{1/2} \quad \textbf{(4.5)}$$

The solar horizontal illuminance is found from:

$$E_{hsun}(n,t)= E_o\cdot f(n)\cdot e^{-c\cdot m(n,t)}\cdot \sin(a(n,t)) \quad \textbf{(4.6)}$$, where:

- $E_o = 127500lx$ is the average solar illuminance on a surface perpendicular to the sun's rays just outside the earth's atmosphere,
- $f(n) = 1+0.0033\cdot\cos(\frac{360\cdot n}{365})$ is a correction factor to account for the elliptical shape of earth's orbit around the sun,
- c is the optical atmospheric extinction coefficient (assumed equal to 0.21 for a clear day),
- $m(n,t) = \frac{1}{\sin(a(n,t))}$ is the relative optical air mass.

The total horizontal illuminance under a CIE clear sky will then be:

$$E_h^{clear}(n,t) = E_{hsky}^{clear}(n,t)+ E_{hsun}(n,t) \quad \textbf{(4.7)}$$

The reflected daylight from the ground and incident on the window is:

$$E_{wgr}(n,t) = F_{w\text{-}gr}\cdot\rho_g\cdot E_h^{clear}(n,t) \quad \textbf{(4.8)}$$

The daylight incident on the window from the sky is:

$$E_{wsky}(n,t) = F_{w\text{-}sky}\cdot E_{hsky}^{clear}(n,t) \quad \textbf{(4.9)}$$

The direct sunlight incident on the window will be:

$$E_{wsun}(n,t) = E_o \cdot f(n) \cdot e^{-c \cdot m(n,t)} \cdot cos(\theta(n,t)) \qquad (4.10)$$

Thus the total amount of daylight incident on the window on a clear day will be:

$$E_w^{clear}(n,t) = E_{wgr}(n,t) + E_{wsky}(n,t) + E_{wsun}(n,t) \qquad (4.11)$$

In order to determine the daylight transmitted into the room, the optimum blind tilt angle for a clear day must be calculated. In the case of clear sky, it is necessary to prevent direct sunlight from coming into the room to avoid glare and high contrast. Thus the blind tilt angle must be adjusted depending on the position of the sun. Since the blinds are horizontal, the solar azimuth has no effect on the daylight transmitted through the blinds and solar altitude is only of interest. Fig. 4.3 shows two successive blinds between the glass panes at a horizontal position (β=90°) and at a random position at an angle β. The distance between the blinds and the width of each blind are both equal to r. Since β is measured starting from the downward position as shown in Fig. 3.7, the angle between the position of the blind and the horizontal will be β-90°. For a random position of the blinds, a direct sunbeam can enter the room (without reflection on the blinds) only for solar altitudes between 0° and α°, as shown in Fig. 4.3. In other words, for a certain solar altitude (time), the minimum blind tilt angle that must be selected in order to prevent direct sunlight from coming into the room is the angle β shown in Fig. 4.3. The reasons for choosing the minimum blind tilt angle are two: first, to allow more daylight into the room (the transmittance values are greater for blind angles closer to horizontal, Fig. 3.15) and second, to allow better view to the outside. It remains to calculate β as a function of solar altitude (time) from the geometry of Fig. 4.3 and determine the optimum blind tilt angle on clear days as a function of solar time and day number.

It is obvious that, because the width of the blinds is equal to the distance between them, for solar altitude angles greater than 45° no direct sunlight is transmitted through the blinds when they are in a horizontal position. Thus, during the hours that α>45°, the blinds will be set at β=90° to maximize the view field to the outside. For all the other cases the calculations must be performed; consider the triangle ABC (Fig. 4.4).

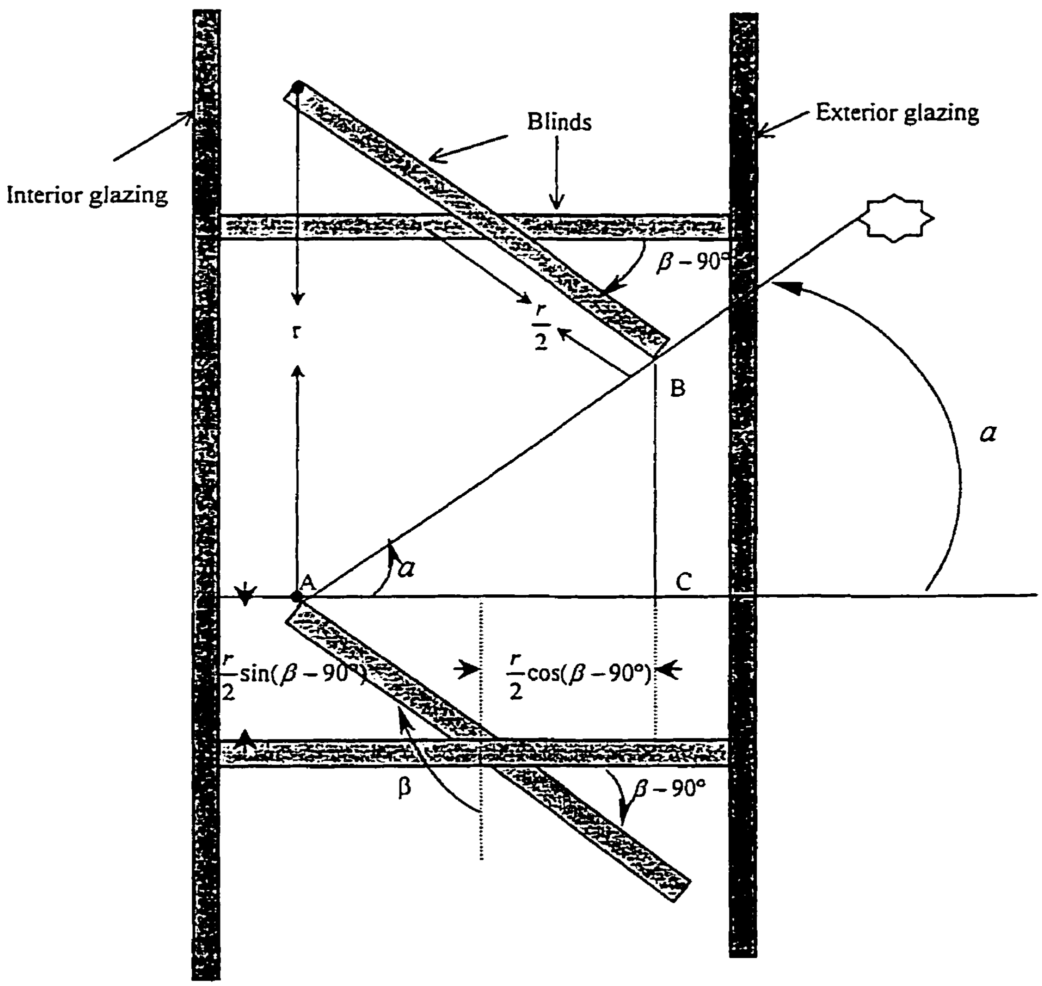


Fig. 4.3. Cross-section of the window system for determination of the optimum blind tilt angle on clear days to avoid glare.

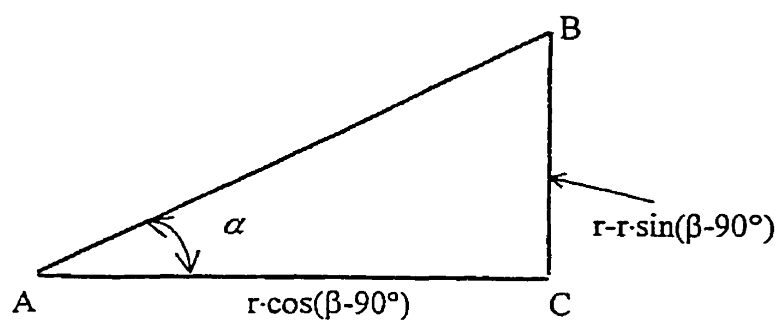


Fig. 4.4. The triangle ABC of Fig. 4.3.

From Fig. 4.4 we obtain:

$$tan(\alpha) = \frac{r - r \cdot sin(\beta - 90^o)}{r \cdot cos(\beta - 90^o)} = \frac{1 - sin(\beta - 90^o)}{cos(\beta - 90^o)} \tag{4.12}$$

Solving this equation for β (APPENDIX E), it is:

$$\beta_{opt}^{clear}(n,t) = 180^o - 2 \cdot \alpha(n,t) \tag{4.13}$$

Thus, the optimum blind tilt angle is selected by the following command:

$$if\ a(n,t) > 45^o,\ then\ \beta_{opt}^{clear}(n,t) = 90^o\ (constant)$$

$$else\ \beta_{opt}^{clear}(n,t) = 180^o - 2 \cdot \alpha(n,t)$$

Since the blind tilt angle and the solar incidence angle are only a function of n and t, the transmittance of Eq. (3.3) may be expressed as a function of n and t. The daylight transmitted into the room on a clear day at any time and day is finally given by:

$$E_{clear}(n,t) = E_w^{clear}(n,t) \cdot \tau_v^{clear}(n,t) \tag{4.14}$$

4.4 Luminous exitances and illuminance on the work plane

The main assumption made at this point is that the window interior surface is considered a diffuse luminous source emitting daylight equally towards all directions in the room. Although this is true for blind tilt angles near 90° (horizontal), it contains an error for blind tilt angles greater than 130° because for such angles the blinds act like small light shelves, illuminating mainly the ceiling and improving the illuminance distribution at the deepest parts of the room. However, the blinds are highly reflective on both sides and thus a significant amount of the transmitted daylight is reflected towards the work plane, the floor and the sidewalls; moreover, this shows that the real situation is better than the results found here and this makes the window system more efficient.

The room is first modelled by 7 surfaces: the window, the wall containing the window, the floor, the ceiling, the back wall and the two sidewalls. Each surface is represented by an index (i) respectively ($i=1..7$). Only the window surface has an initial luminous exitance. The luminous exitance of the window (the total luminous flux density leaving the window) is equal to $E_{overcast}(n,t)$ for the overcast case and $E_{clear}(n,t)$ for the clear case (the daylight that is transmitted into the room for each case). The main assumption is that the window has a uniform luminance all over its surface; however, from the results presented in paragraph 3.3, this much is true; moreover, the window is anyway assumed a uniform diffuse luminous source, as well as the other interior surfaces are.

In the following calculations, it is convenient to work with matrices. The final luminous exitances of all interior surfaces after multiple reflections in the room must be next calculated. First, the form factors between all interior surfaces are found. The form factor F_{12} between two surfaces A_1 and A_2 is the ratio of average illuminance on A_2 produced by the flux received directly from A_1 due to the luminous exitance of A_1.

For two rectangular parallel surfaces with dimensions l and w at a distance h (Fig. 4.5), the form factor is given by:

$$F_{ij}=\frac{2}{\pi\cdot s\cdot z}\cdot\left\{0.5\ln\left(\frac{(1+s^2)\cdot(1+z^2)}{1+s^2+z^2}\right)+z\cdot\sqrt{1+s^2}\cdot\tan^{-1}\left(\frac{z}{\sqrt{1+s^2}}\right)+s\sqrt{1+z^2}\cdot\tan^{-1}\left(\frac{s}{\sqrt{1+z^2}}\right)-z\cdot\tan^{-1}(s)-s\cdot\tan^{-1}(z)\right\} \quad (4.15)$$

where $s=w/h$ and $z=l/h$.

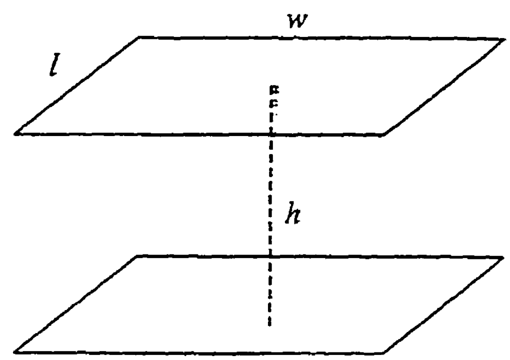


Fig. 4.5. Two opposite rectangular surfaces (w, l) at distance h.

For two rectangles at angle of 90° and havīng one common edge (Fig. 4.6), the form factor is given by:

$$F_{ij}=\frac{1}{\pi\cdot s}\cdot\left[s\cdot\tan^{-1}\left(\frac{1}{s}\right)+z\cdot\tan^{-1}\left(\frac{1}{z}\right)-\sqrt{s^2+z^2}\cdot\tan^{-1}\left(\frac{1}{\sqrt{s^2+z^2}}\right)+0.25\ln\left\{\frac{(1+s^2)\cdot(1+z^2)}{1+s^2+z^2}\cdot\left[\frac{s^2\cdot(1+s^2+z^2)}{(1+s^2)\cdot(1+z^2)}\right]^{s^2}\cdot\left[\frac{z^2\cdot(1+s^2+z^2)}{(1+s^2)\cdot(1+z^2)}\right]^{z^2}\right\}\right]$$

where: $s=w/l$, $z=h/l$. **(4.16)**

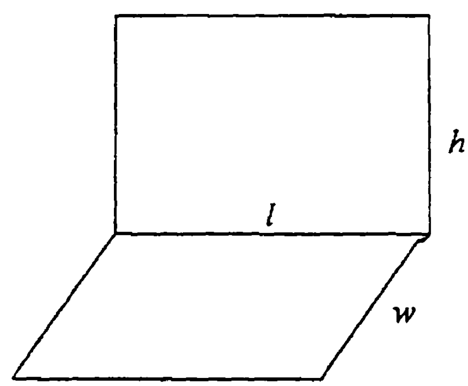


Fig. 4.6. Two perpendicular rectangular surfaces with one common edge.

The form factors between all other surfaces are found by discretizing each surface in smaller surfaces and using the following equations (APPENDIX B, Athienitis, 1997):

$\sum_j F_{ij} = 1$ *(energy conservation)*

$A_i \cdot F_{ij} = A_j \cdot F_{ji}$ *(reciprocity)*

$F_{ii}=0$ *(a surface cannot emit to itself)*

$F_{ij}=F_{jk}$ *(symmetry)*

Using form factors, the final luminous exitance of each interior surface (M_i) may be calculated by:

$$M_i = M_{oi} + \rho_i \cdot \Sigma M_j \cdot F_{ij} \quad \textbf{(4.17)}, \text{ or}$$

$$M_{oi} = M_i - \rho_i \cdot \Sigma M_j \cdot F_{ij} \quad \textbf{(4.18)}$$

where ρ is the surface reflectance vector. This system can be written in matrix form as follows:

$$\boldsymbol{M_o = (I\text{-}T) \cdot M} \quad \textbf{(4.19)}$$

where M_o is the initial luminous exitance matrix, I is the 7x7 identity matrix and T is a matrix whose elements are equal to:

$$T_{ij} = \rho_i \cdot F_{ij} \quad \textbf{(4.20)}$$

The matrix containing the final luminous exitances of the interior surfaces as a function of solar time and day number is calculated from:

$$\boldsymbol{M(n,t) = (I\text{-}T)^{-1} \cdot M_o(n,t)} \quad \textbf{(4.21)}$$

The next step is to select representative points on the work plane (if not calculate for the whole work plane surface grid) and calculate the illuminance on them. Four points are selected (A, B, C and D) at the work plane height (0.8m from the floor), 2.5m from both the left and right wall and at distances from the window given by:

A: 0.94m, B: 1.88m, C: 2.82m, D: 3.76m (Fig. 4.2).

In order to determine the illuminance at the selected points, the configuration factors between each of the points and all interior surfaces of the room must be calculated. The configuration factor c_{S1A} is defined as the ratio of the illuminance at a differential area (or point A) produced by the flux received directly from a surface (S_1) due to the luminous exitance of S_1. The configuration factor between a point (dA) and a rectangular surface with dimensions a and b at a distance c from the point is given by (Murdoch, 1985):

$$C_{dA\text{-}S_1} = \frac{1}{2\cdot\pi}\cdot\left\{\frac{x}{\sqrt{1+x^2}}\cdot\tan^{-1}\left(\frac{y}{\sqrt{1+x^2}}\right)+\frac{y}{\sqrt{1+y^2}}\cdot\tan^{-1}\left(\frac{x}{\sqrt{1+y^2}}\right)\right\} \quad (4.22)$$

if the surface is perpendicular to the dA, and by:

$$C_{dA\text{-}S_1} = \frac{1}{2\cdot\pi}\cdot\left\{\tan^{-1}\left(\frac{1}{y}\right)-\frac{y}{\sqrt{x^2+y^2}}\cdot\tan^{-1}\left(\frac{1}{\sqrt{x^2+y^2}}\right)\right\} \quad (4.23)$$

if the surface is parallel to dA, where $x=a/c$ and $y=b/c$. Using the above equations, the configuration factors C_{Ai}, C_{Bi}, C_{Ci} and C_{Di} between points A, B, C, D and all the interior surfaces of the room are found (APPENDIX C).

Finally, the horizontal illuminance on each of the four selected points is computed as a function of solar time and day number:

$$E_{A,B,C,D}(n,t) = \sum M_i(n,t)\cdot C_{Ai,Bi,Ci,Di} \quad (4.24)$$

This equation gives the illuminance profile of the room at the work plane height for all the working hours of the year and provides the necessary results to determine the daylight quantity and uniformity in the office and to estimate the possible energy savings. In order to reduce the computation time, which is for 7(hr)x365(days) and simplify the calculations, the following approach was considered: because the angle of incidence (θ) changes 3-4 degrees within 15 days, the 15th day of each month is selected and the calculations are done for all the times of these average days. We assume that the movement of the sun in all the other days of each month is identical (4 degrees error in the angle of incidence result in 5-10lx error on the final work plane illuminance, which is negligible) and thus we perform the calculations for only 12 days of the year. Each of the 12 days is representative of the respective month with very good accuracy. In this way, eventually there are four matrices for 7(hr)x12(months), containing the illuminance on each of the four selected points throughout the year.

Representative simulation results are shown in the following figures.

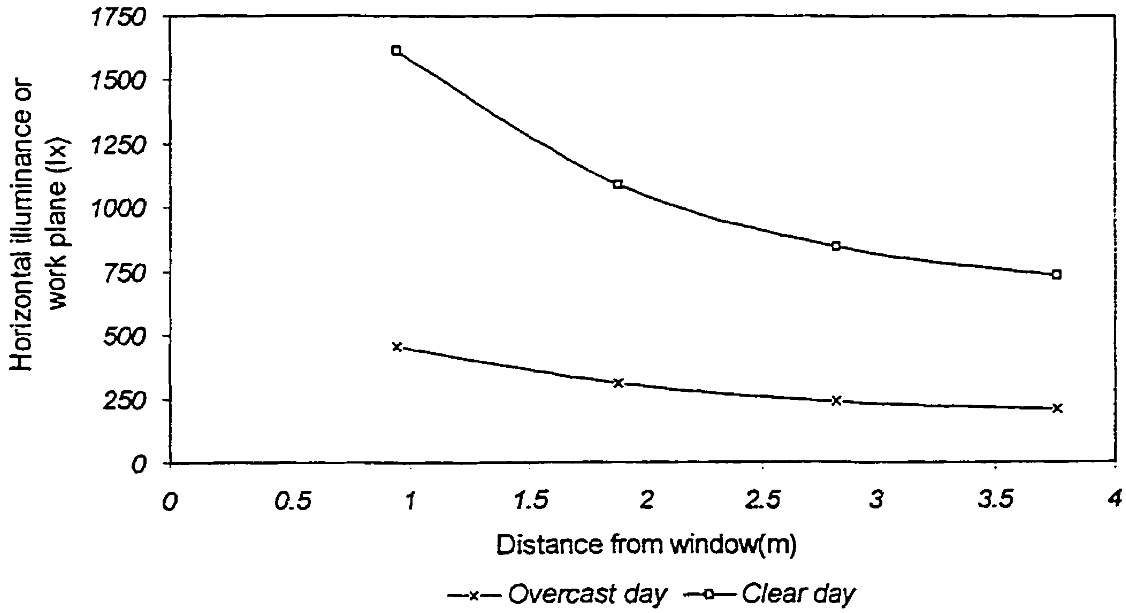


Fig. 4.7. Illuminance distribution on the work plane, on a typical overcast and clear day in January at 9am.

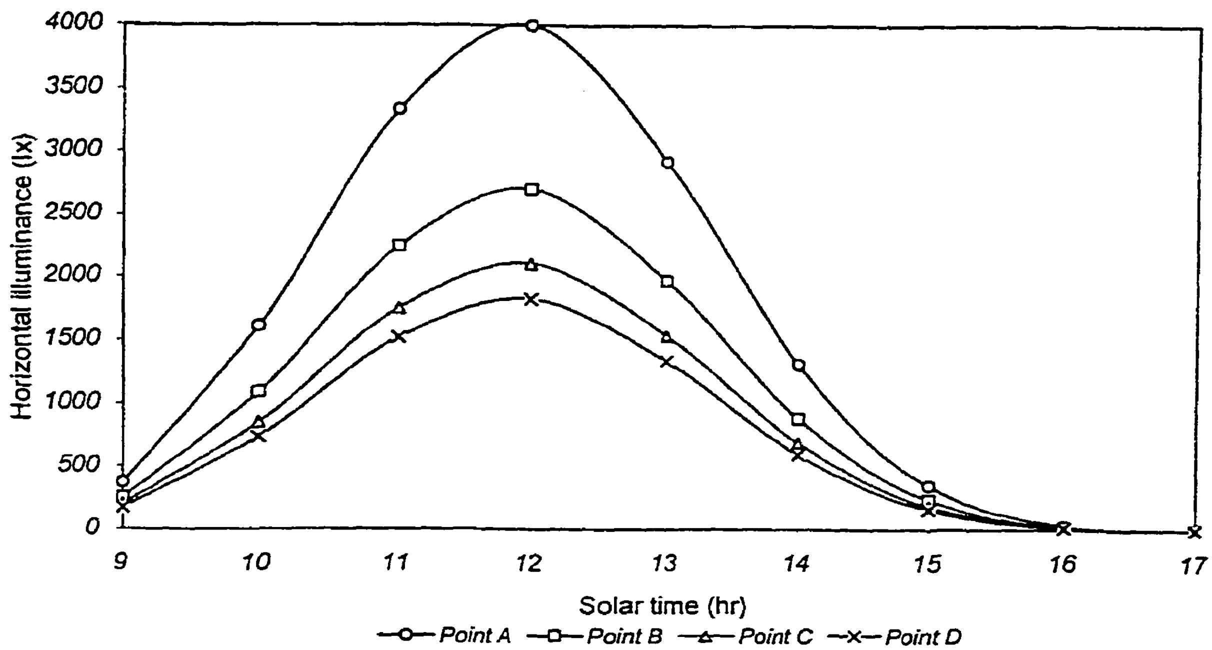


Fig. 4.8. Horizontal illuminance on the selected points during the working hours of a clear day in January.

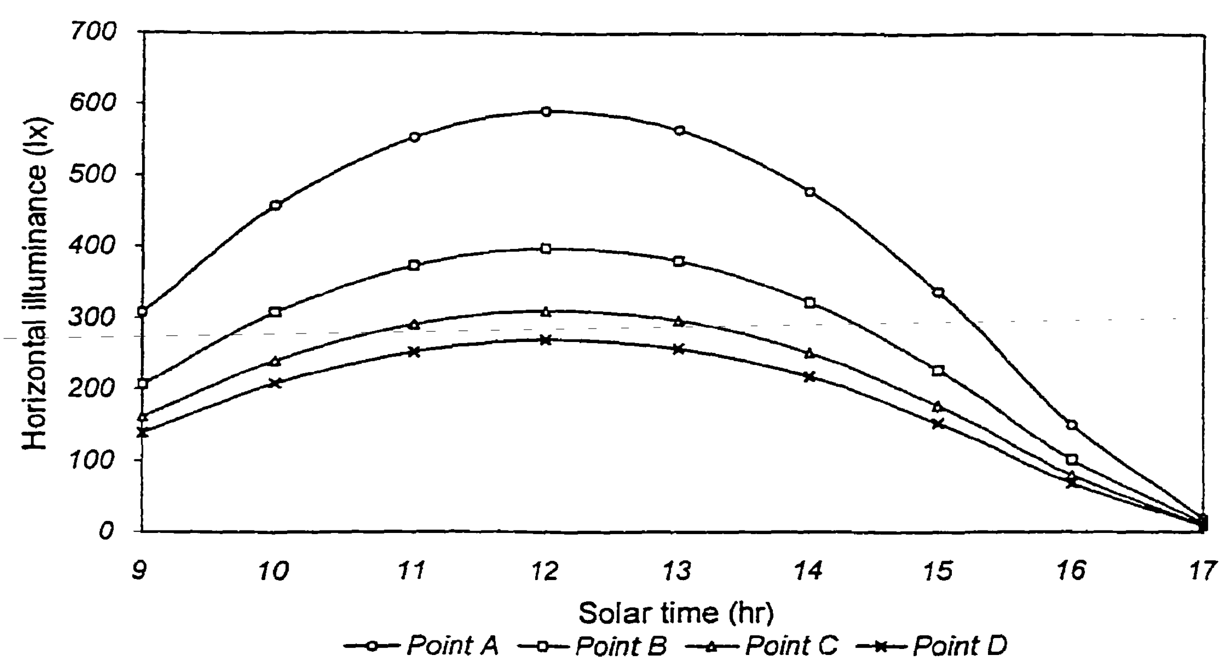


Fig. 4.9. Horizontal illuminance on the selected points during the working hours of an overcast day in January.

4.5 Verification of the accuracy of the method

Since there are no building simulation programs or other software available to predict the illuminance in a room with a window with integrated motorized blinds, a comparison with experimental measurements is necessary and preferable. The experimental measurements were performed with a movable lux meter at different positions in the test room (respective to points A and B in the above simulation) and for different and solar incident angles (and, automatically, for different blind tilt angles). The reflectances of the test room interior surfaces are the following: wall reflectance: 65%, ceiling reflectance: 80% and floor reflectance: 20%. The dimensions of the test room are smaller than those of the simulated office, so the programs for the calculation of form factors and configuration factors had to be modified. Based on measured exterior illuminances of 5800 lx (overcast) and 47000 lx (clear), the results of the measurements showed that: on overcast days, the simulation results overestimate the illuminance on the work plane about 10%-11%, while on clear days, the simulation results overestimate the measured illuminance values about 1%-13%. The difference is not significant for design purposes and a portion of it may be due to wrong estimation of the test room interior reflectances. Of course, the assumption that the window is a Lambertian source results in the largest portion of the difference in the illuminances. The blinds reflect a lot of daylight towards the ceiling and thus more daylight is incident on point B than the predicted (and less on point A), as shown in Fig. 4.11.

The difference between the illuminance values predicted by the simulation and the illuminance values measured is shown below, for the case of overcast day and the case of clear day, respectively.

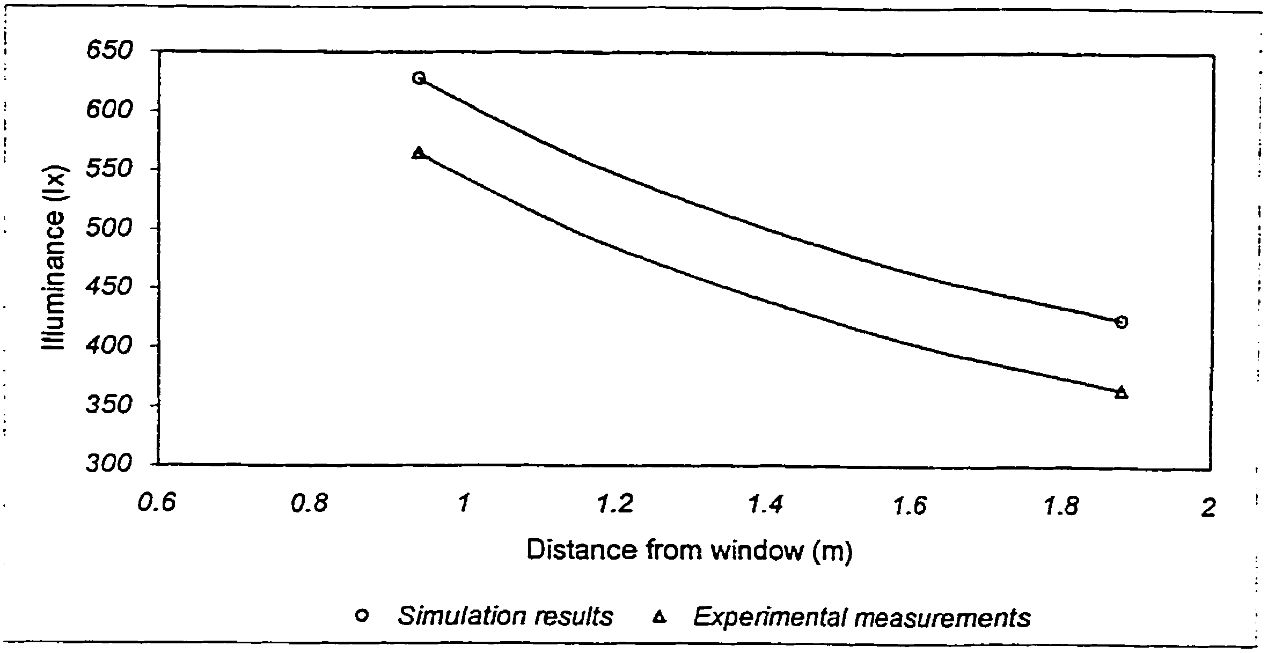


Fig. 4.10. Comparison of predicted and measured values of illuminance for overcast day.

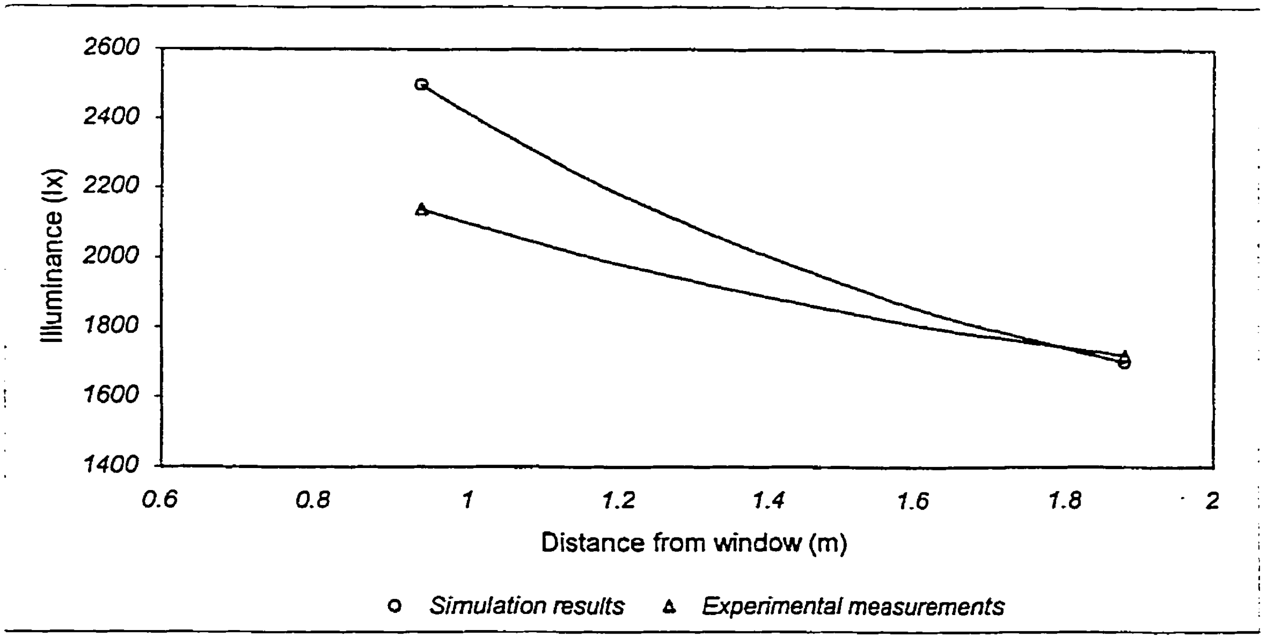


Fig. 4.11. Comparison of predicted and measured values of illuminance for clear day.

4.6 Energy savings from simultaneous control of the blinds and dimming of electric lights

The blinds are automatically operated and, based on the results of Eq. (4.24), the electric lights are automatically dimmed in order to improve the illuminance distribution in the office, provide the necessary illumination, if any, in order to reach a pre-selected setpoint -500lx- and at the same time save electrical energy.

The luminaires selected for this simulation were chosen from a wide variety listed in the Lumen Micro 7.0 software. Each luminaire consists of four 196W rapid start fluorescent lamps with 3850 initial lumens per lamp. Using the coefficients of utilization method (and checked with Lumen Micro software), the required number of luminaires is two, in order to have 500 lx on the working plane (target illuminance). The selected position of the two luminaries is the following: the first (L_1) is above point B (1.88m from the window) and the second (L_2) is above point D (3.76m from the window). Then, using the candela distribution tables provided by the manufacturer, the illuminance on each of the four points on the work plane is calculated when each luminaire is 100% on. It is assumed that the dimming is not continuous (which is more expensive), but it can be done in four possible levels: 25%, 50%, 75% and 100% of the output of the lamps. Knowing the illuminance on the four points throughout a year only with natural daylight, the illuminance required to reach 500lx on all points can be found.

Based on these results, the dimming level for L_2, dim_2 is determined (which is deeper in the room):

if $E_D(n,t)$ 500lx then dim_2=0%

else determine the dimming level of L_2 (25%, 50%, 75%, 100%) depending on the lx required to complete 500lx on point D.

Knowing the dimming level of L_2, the new increased illuminance values on each of the four points is found. If there are still working hours in the year for which the illuminance on points A, B or C is lower than 500lx, L_1 is dimmed, too (based on the illuminance on point B:

if $E_B(n,t)$ 500lx then dim_1=0%

else determine the dimming level of L_1 (25%, 50%, 75%, 100%) depending on the lx needed to complete 500lx on point B.

In this way, the illuminance on B is always more than 500lx. Point C is between the two luminaries and, with L_1 dimmed, it receives always more than 500lx, too. The same happens for point A, except for an hour (4pm-5pm) in the evening. The dimming level is calculated for all times and days in the year in matrix form (same as the illuminance matrix). These calculations are done for both clear days (Appendix F) and overcast days (Appendix D). Some results are shown in the following figures.

On overcast days, this dimming strategy improves significantly the illuminance distribution in the office and ensures that there are always more than 500lx on each of the four points (Fig. 4.12, Fig. 4.13). On clear days, where there is not enough daylight after 3pm, the problem is eliminated and the illuminance distribution is also improved (Fig. 4.14, Fig. 4.15). Lights remain off from 930am to 2pm. December is selected for these samples, since the lowest illuminance values occur in December and January.

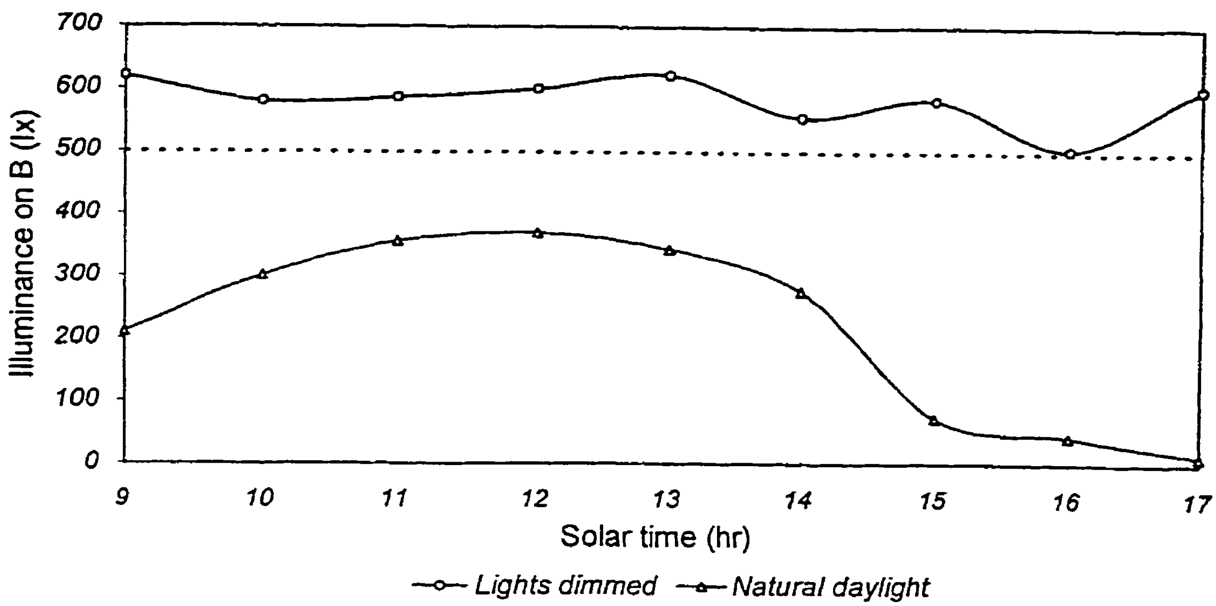


Fig. 4.12. Horizontal illuminance on point B (1.88m from the window) on a typical overcast day in December, with natural daylight only and with dimmed electric lights.

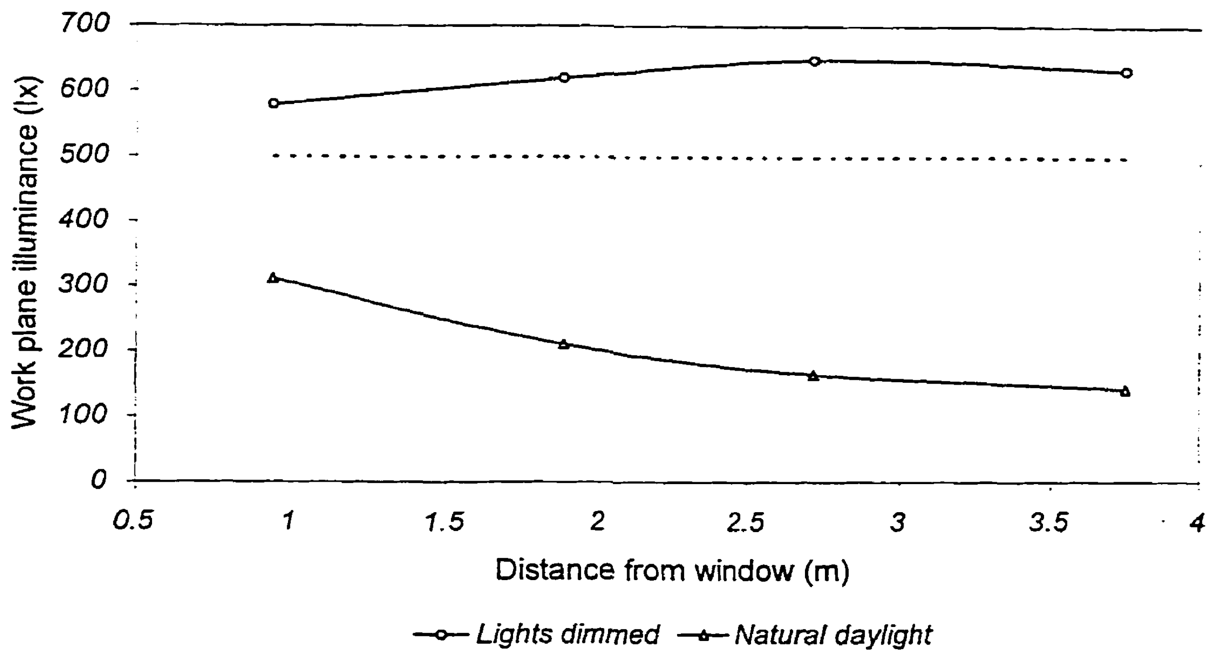


Fig. 4.13. Illuminance on the work plane at 9am on an overcast day in December.

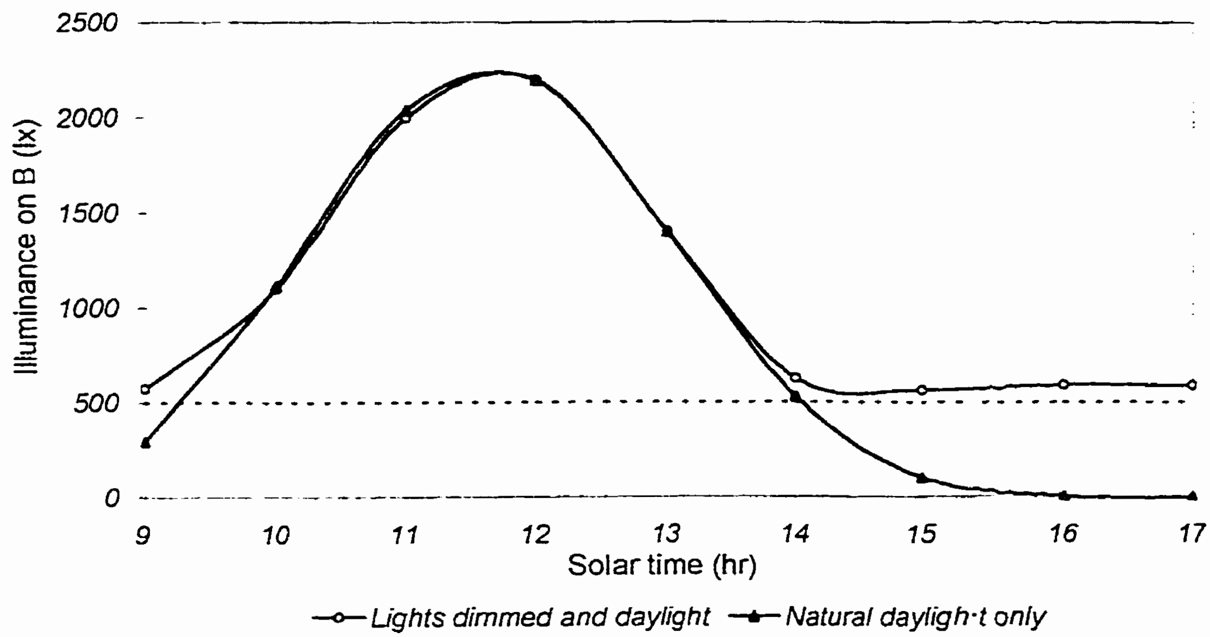


Fig. 4.14. Horizontal illuminance on point B on a typical clear day in December.

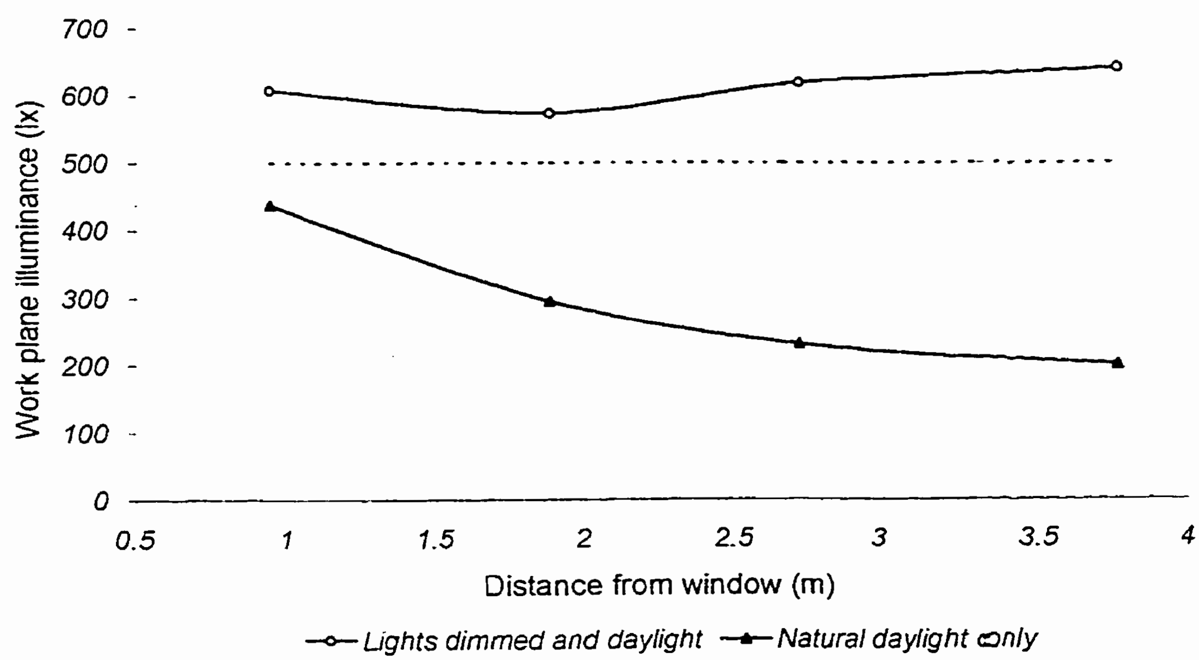


Fig. 4.15. Illuminance on the work plane at 9am on a typical clear day in December.

The results from the calculations of the dimming levels throughout the year are the following: on clear days, L_1 and L_2 are not 100% on except for one hour (4pm-5pm), where L_1 is dimmed at 75% and L_2 (which is deeper in the room) is 100% on (Fig.4.16). This happens for all the months of the year except for December, where the lights are dimmed during all the working hours of the day. On overcast days, L_1 is dimmed during all the working hours in the winter and only from 4pm to 5pm during the other months, but L_2 needs to be dimmed during all months, as shown in Fig. 4.16. L_2 is responsible for most of the electricity consumption on overcast days. In the summer it is kept off between 10am and 2pm, while in the other seasons it needs to be dimmed all the time between 9am and 5pm.

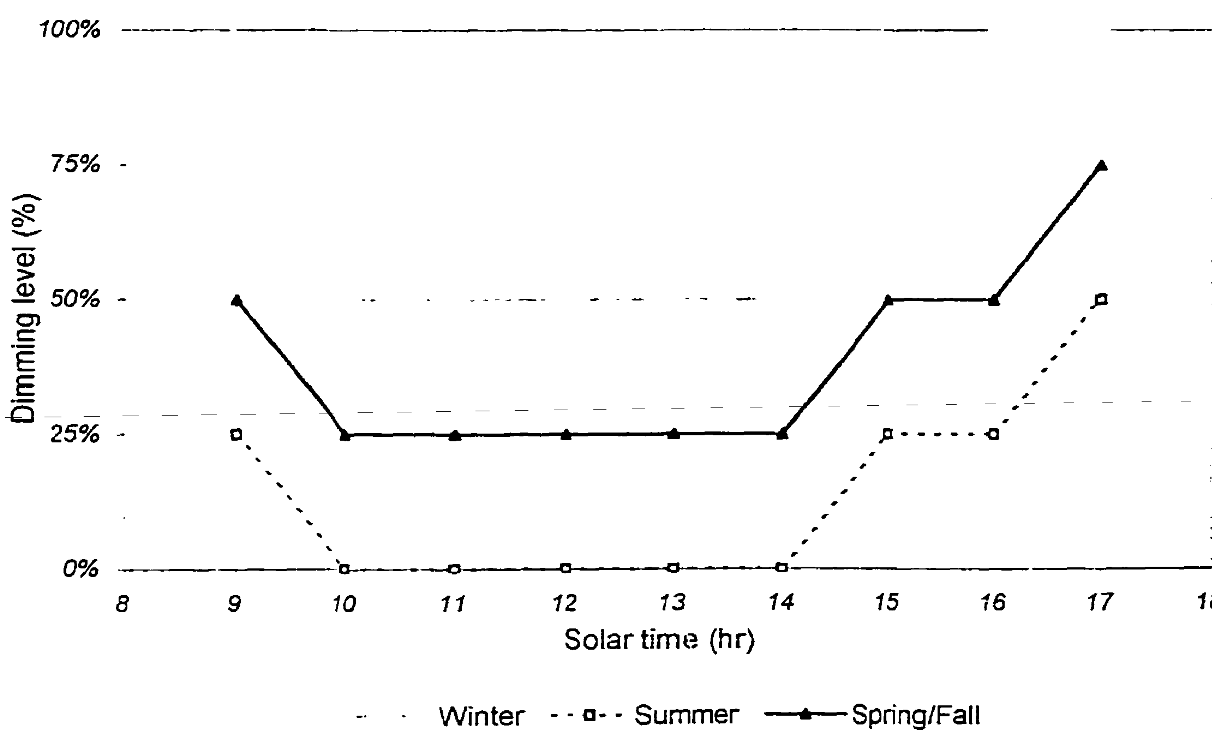


Fig. 4.16. Dimming levels of luminaire L_2 (3.76m from the window) during all seasons of the year on overcast days.

Generally, the simulation of simultaneous control of the blinds and dimming of the lights showed that:

- On overcast days, L_1 is kept off during the 65% of the working hours and L_2 is kept off during the 19.4% of the working hours of the year.
- On clear days, L_1 is kept off during the 73.1% of the working hours and L_2 is kept off during the 70.3% of the working hours of the year.
- On overcast days, L_1 is never set at 100% output and L_2 is 100% on only for 9.2% of its operating hours in a year
- On clear days, L_1 is never set at 100% output and L_2 is 100% on only during the 68.7% of its operating hours in a year.

Furthermore, comparing with an office space where neither dimming of the lights nor on/off operation is available (lights are on at 100% output during all the working hours of the year), the energy savings due to electrical lighting using the window system and the dimming methodology presented -with the assumed 60W lamps- above reach 76.2% for overcast days and 87.2% for clear days, annually.

The comparison with a common double-glazed window with no movable shading devices is interesting. On overcast days, the common window allows more daylight into the space (daylight is not blocked or reflected on the blinds), as expected. However, on clear days, a shutter/curtain must be used to block direct sunlight and as a result electrical lights have to be 100% on during all the working hours. Thus the energy savings using the window system with integrated motorized blinds and simultaneously dimming the lights are certainly greater.

Instead of the motorized louvers, a motorized roller blind could also be used, but the results would be different in that case. The roller blind can be completely opaque or semi-transparent, and it is a homogeneous device. On overcast days, assuming that the roller blind is fully open, the energy savings are again better. On clear days though, the roller blind should close at a certain portion depending on the position of the sun. Thus it hides a significant portion of the sky to the interior space. As a result, it minimizes the view field to the outside and reduces the illuminance values in the room; consequently, more electrical energy is required for lighting.

On the other hand, the blind is a discrete device. The horizontal blinds allow daylight to be transmitted in many different ways: it can be reflected by any of the blinds (in quite complicated combinations) coming from all directions (sky, sun, ground) and transmitted easily through the spaces between the blinds. Most of it is reflected towards the ceiling and illuminates the deeper parts of the space. The illuminance values are certainly greater; the view to the outside is better (the spaces between the louvers are multi-purpose) and the energy savings are greater. Of course, it all depends on the type of motorized venetian blinds/roller blind used in each case. The roller blind can be semi-transparent and allow enough daylight in the room on clear days; then again, the blinds can be highly reflective and produce a more luminous environment. The shape, the size, the material and the finish of such shading devices are important factors. Optimization of both systems is necessary and human psychological effects must be also taken into account.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A methodology for detailed calculation of room illuminance levels and light dimming in an office space with motorized blinds integrated in an advanced window is presented. The transmission characteristics of the window were determined with full-scale experimental measurements in an outdoor test-room. Using the transmittance equations developed from the experiments, a simulation of a typical office space with such a window was performed, to investigate the daylighting efficiency of the system and to estimate the energy savings due to dimming of electric lighting. The major assumption made in the simulation is that the inside surface of the window acts like a diffuse luminous source, emitting diffuse daylight uniformly towards all directions in the room; it was shown that this assumption is justified for design and control.

The advanced window system studied above has complex optical properties; the blinds are highly reflective on both sides and thus daylight is reflected, transmitted and scattered in many different directions. Direct solar radiation is always blocked by choosing the appropriate blind tilt angle to avoid glare and high contrast, which can cause discomfort to the occupants. This is a rational assumption for an office space. However, constraints are different for different types of buildings and interior spaces. In office spaces, such as the one considered in the above simulation, daylight optimization and reduction of he cooling load dictate the position of the shading device. In the case of solar houses, maximum solar gains are desirable to minimize heating energy consumption. In the latter case, the amount of solar radiation present in the space can be determined using the solar radiation transmittance equations. The detailed special distribution of the direct solar gains may be also calculated (Athienitis & Sullivan, 1985).

The size and the orientation of the window are critical factors; this type of window is rather suitable for south (or near south) facing facades of offices, as well as for large skylights.

The characteristics of the blinds are also of major importance; the dimensions of the blinds, the distance between them and the finish of the blinds determine the transmittance of this shading device.

The results of the simulation showed that this window is may provide complete protection against direct solar radiation and glare during all the working hours of the year. It allows the maximum possible amount of daylight into the room while maximizing the viewing field to the outside. The control of the shading device combined with simultaneous control of dimming of the electrical lights can increase the daylight level at the deeper parts of a room, improve the daylight uniformity within a space and ensure a good quality visual environment. At the same time, it blocks direct sunlight during the cooling season and the potential energy savings due to electricity consumption for lighting are high (76.2% on overcast days and 87.2% on clear days).

6.2 Recommendations and possible extensions of current work

This project is a daylighting study and evaluation of an advanced window. Although the control algorithm presented seems to result in efficient use of the system, the combination of a daylighting study with a building thermal analysis tool is always necessary in order to determine the optimal operation of the shading devices and HVAC system together. A possible study about the U-value of the window system, as a function of the blind tilt angle would be a useful tool for the thermal evaluation of this advanced window.

In this work, the objective was to automatically operate the blinds as an occupant would if he/she were to constantly monitor the interior and exterior lighting conditions. In the simulation, general equations were applied to predict the incident daylight on the exterior surface of the window. In reality, however, an exterior sensor should detect the illuminance level outside to ensure accuracy and quick response; then a microprocessor shall decide if the conditions are clear or overcast, based on a pre-built illuminance level database for all the months in the year. In the case when the conditions are neither clear nor overcast (partly cloudy day), the building automation system should determine the type of sky conditions at regular times, based on the readings of the exterior sensor. Following a control algorithm similar to the one presented, it will determine the position of the shading device (eliminating glare) and control the movement of the blinds on a real-time basis. At the same time, the electrical lights will be dimmed at the optimal level, in order to ensure adequate lighting and good visual conditions for the occupants.

In several cases, the illuminance on the work plane found by the simulation reaches very high levels (it can reach more than 5000 lx in some hours during clear summer days). This is not desirable, both because it can lead to glare (although all the light is diffuse) and visual discomfort, and also because it would increase the cooling load for the space. Thus, for such days, the control algorithm should be modified to allow less daylight in the room. Note that the considered office is unfurnished, with highly reflective surfaces. Therefore, the interreflected component was overestimated, compared to a real situation.

The analytical method for calculating the illuminance on several points on the work plane (presented in chapter 4) although accurate enough, may be modified to allow the calculation of illuminance on a large number of points on the work plane (or elsewhere in the room), if extremely detailed calculations are to be achieved (for research purposes). The development of a detailed simulation software tool that could handle this type of shading devices and link their optical and thermal characteristics with their daylighting and thermal performance in closed spaces would be an extremely useful tool for building design.

The solution of the optimization problem of the configuration and control of motorized shading devices is a field in which much research needs to be done. Varying the physical and optical properties of the blinds and performing a sensitivity analysis for optimum operation are desirable. Also, the experimental comparison of this system with other advanced motorized shading devices would be necessary in order to evaluate the optimal combined daylighting and thermal performance.

The application of the control algorithm in the operation of the automated venetian blind in synchronization with a real dimmable electric lighting system is desirable; experimental measurements with sensitivity analysis reflect the real situation and may show different aspects of the problem.

Finally, using such a building automation system, human control is minimized; however, in some cases this is not desirable; several psychological and physiological factors have to be considered: privacy, possible noise effects, the reduction of the viewing field, unstable daylighting conditions and the continuous movement of the shading device can be some of the reasons that may cause discomfort and disruption to occupants. In many cases, people may wish to have complete control of the operation of shading systems. This may be accommodated by allowing optional manual operation of the shading device and/or HVAC system components. In this way, the semi-automatic simultaneous dynamic combined control of building envelope components, electric lighting systems and HVAC systems may determine the optimal operation of all subsystems in order to achieve minimization of energy consumption while maintaining good human comfort.

REFERENCES

1. Aleo F., Sciuto S., Viadana R., "Solar transmission measurements in outdoor conditions of non-homogeneous shading devices", Proceedings of the European conference on energy performance and indoor climate in buildings, Lyon, France, 1994.

2. Argiriou A., Asmakopoulos D., Balaras C., "Daylight techniques in buildings-Reference handbook", European Commission Directorate General XVII for Energy ALTENER Programme, Athens, 1997.

3. Athienitis K. A., Building thermal analysis, Mathcad Electronic handbook, Mathsoft Inc., Boston, USA,1998.

4. Athienitis K. A., Tzempelikos A., "A methodology for detailed calculation of room illuminance levels and light dimming in a room with motorized blinds integrated in an advanced window", submitted for the eSim 2001 building simulation conference, Ottawa, June 2001.

5. Athienitis K. A., Santamouris M., "Thermal analysis and design of passive solar buildings", James & James Pub., London, UK, 1999.

6. Athienitis K. A., Sullivan F. H., "Efficient method for determination of solar radiation absorbed by each room interior surface and effects", Proceedings of the 9th Biennial Congress of the International Solar Energy Society (INTERSOL '85), Montreal, Canada, 1985.

7. ASHRAE Handbook-Fundamentals, Ch. 29, Atlanta, Georgia, 1997.

8. Baker N., Fanchiotti A., Steemers K., "Daylighting in Architecture-A European Reference Handbook", Commission of the European Communities, Directorate-General XII for Science and Development, James & James Pub., 1993.

9. Bauman S. F., Place W. J., Andersson B., "The experimentally measured performance of a linear roof aperture daylighting system", ASHRAE Trans. Vol. 93, Pt 1, 1987.

10. Beck A., Körner W., Gross O., Fricke J., "Making better use of natural light with a light-redirecting double-glazing system", Solar Energy 66 (3), pp. 215, 1999.

11. Bryan H., Clear R., "Calculating daylight illuminance with a programmable hand calculator", Journal of the Illumination Engineering Society, Vol. 10 (4), pp. 219, 1981.

12. Chauvel P. et al, "Glare from windows: current views of the problem", BRE, London, HMSO. 1980.

13. CIE Publication 40, "Calculations for interior lighting-basic method", Paris, 1978.

14. Coch H., Isalgue A., "Sun ducts: new design and applications", World Renewable Energy Congress, Oxford, UK, 2000.

15. Cogan S. et al, "Optical switching in complementary electrochromic windows", Proceedings of SPIE conference, Vol. 692, San Diego, California, 1986.

16. Courret G., Paule B., Scartezzini J. L., "Anidolic zenithal openings", Proceedings of the European conference on energy performance and indoor climate in buildings, Lyon, France, 1994.

17. DiLaura D., "A new technique for intereflected component calculations", IES Journal, Vol. 8, pp. 53, 1979.

18. Gillette G., Kusuda T., "A daylighting computation procedure for use in DOE-2", IES Journal, October 1982.

19. Gillette G., "A daylight model for building energy simulation", NBS Building Science series 152, Washington, USA, 1983.

20. Gillette G., Pierpoint W., "A general illuminance model for daylighting availability", IES tecncal conference, Atlanta, USA, 1982.

21. Goral C., Greenberg D., Torrance K., Battaile B., "Modelling the interaction of light between diffuse surfaces", Computer Graphics, Vol. 18 (3), 1984.

22. Harrison A., Coombes C., "Angular distribution of clear sky short wavelength radiance", Solar Energy, Vol. 40 (1), pp. 57, 1988.

23. Hooper F., Brugner A., Chan C., "A clear sky model of diffuse sky radiance", Trans. of ASME Journal of Solar Energy Engineering, Vol. 109 (1) CIE, 1987.

24. IES, lighting Handbook, Reference Volume, IESNA, New York, 1984.

25. Karlsson J., Roos A., "Modelling the angular behaviour of the total solar energy transmittance of windows", Solar Energy, Vol. 69 (4), pp. 321, 2000.

26. Kaufman J., Haynes H., IES lighting handbook, Vol. 1, New York, 1981.

27. Kittler R., "Standardization of outdoor conditions for the calculation of daylight factor with clear skies", Proceedings of the CIE Intercessional Conference on Sunlight, Newcastle, Rotterdam, 1965.

28. Kittler R., "A universal calculations method for simple predetermination of natural radiation on building surfaces and solar collectors", Building and Environment, Vol. 16 (3), Great Britain, 1981.

29. Lee J. et al, "Thermochromic materials research for optical switching", Proceedings of SPIE Conference, Vol. 692, San Diego, California, 1986.

30. Lee S. E., Selkowitz E. S., "The design and evaluation of integrated envelope and lighting control strategies for commercial buildings", ASHRAE Trans. 101 (1), pp. 326, 1995.

31. Lee S. E., DiBartolomeo L. D., Selkowitz E. S., "Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office", Energy and Buildings, Vol. 29, pp. 47, 1998.

32. Littlefair P., "Modelling daylight illuminances in building environmental performance analysis", IES Journal, Vol. 21, pp. 25, 1992.

33. Littlefair P., "Developments in innovative daylighting", BRE report, 2000.

34. Longmore J., BRS daylight protectors, Garston, Watford, UK, 1967.

35. Lorenz W., "A glazing unit for solar control, daylighting and energy conservation", Solar Energy, Vol. 70 (2), pp. 109, 2001.

36. Lorenz W., "Design guidelines for a glazing with seasonally dependent solar transmittance", Solar Energy, Vol. 63 (2), pp. 79, 1998.

37. Lynes J., "Principles of natural lighting", Elsevier, London, 1969.

38. Michel L., Roecker C., Scartezzini J-L., "Performance of a new scanning sky simulator", Lighting Research and Technology, Vol. 27 (4), pp. 197, 1995.

39. Molina L. J.,Maestre R. I., Lindawer E., "A model for predicting the angular dependence of the optical properties of complex windows including shading devices", Proceedings of PLEA 2000, Cambridge, UK, 2000.

40. Moon P., Spencer D., "Illumination from a non-uniform sky", IES journal, Vol. 37, pp. 707, 1942.

41. Murdoch B. J., "Illumination Engineering-from Edison's Lamp to the Laser", Macmillan Pub., New York 1985.

42. Muller H. O. F., Capelle A., "Transparent shading devices with concentrating holograms and photovoltaics", World Renewable Energy Congress VI, Oxford, 2000.

43. Perez R., Seals R., Michalsky J., "All weather model for sky illuminance distribution-preliminary configuration and validation", Solar Energy, Vol. 50, pp. 235, 1993.

44. Muller H. O. F., "Application of holographic optical elements in buildings for reduced energy consumption and improved indoor climate", Proceedings of the European conference on energy performance and indoor climate in buildings, Lyon, France, 1994.

45. Pilkington brothers, "Windows and Environment", 1969.

46. Pucar M., "Application of reflecting louvers and convex reflecting parapet for illuminating north sides of neighbouring buildings", World Renewable Energy Congress VI, Oxford, 2000.

47. Rheault S., Carle Y., Bilgen E., "A simplified design tool for window with automated venetian blinds used in greenhouses", Proceedings of the ISES Solar World Congress, Hamburg, Germany, 1987.

48. Sceatzle D., "Computer controlled window blinds", Proceedings of the 15th AS/ISES National Passive Solar Conference, Texas, USA, 1990.

49. Steemers K., "Integrating shading and daylighting for energy efficiency and comfort", Proceedings of the European conference on energy performance and indoor climate in buildings, Lyon, France, 1994.

50. Tsangrassoulis A., "Contribution in the mass flow and visible radiation flow phenomena through partly opened openings", PhD Thesis, Department of Applied Physics, University of Athens, 1997.

51. Tsangrassoulis A., Santamouris M., Asimakopoulos D., "Theoretical and experimental analysis of daylight performance for various shading systems", Energy and Buildings, Vol. 24, pp. 223, 1996.

52. Tsangrassoulis A., Santamouris M., Geros V., Wilson M., Asimakopoulos D., "A method to investigate the potential of south-oriented vertical surfaces for reflecting daylight onto oppositely facing vertical surfaces under sunny conditions", Solar Energy, Vol. 66 (6), pp. 439, 1999.

53. Tzempelikos A., "Simulation of different sky luminance distributions with the aid of a new artificial sky", Undergraduate Thesis, Department of Physics, Section of Applied Physics, University of Athens, Greece, 1999.

54. Unicel Inc. Manual of Vision Control Window, Montreal, Canada.

55. Van Tichelen P., De Laet I., Taeymans F., Adams F., "Energy savings from the EE-SULK daylighting system", World Renewable Energy Congress VI, Oxford, 2000.

56. Vartiainen E., Peippo K., Lund P., "Daylight optimization of multifunctional solar facades", Solar Energy, Vol. 68 (3), pp. 223, 1999.

57. Vine E., Lee E., DiBartolomeo D., Selkowitz S., "Office worker response to an automated venetian blind and electric lighting system: a pilot study", Energy and Buildings, Vol. 28, pp. 205, 1998.

58. Wagner A., Frenzel B., "The influence of translucent insulation in windows on the daylighting level and the energy demand of an office room", Proceedings of the European conference on energy performance and indoor climate in buildings, Lyon, France, 1994.

59. Waldram P., "A measuring diagram for daylight illumination", Batsford Pub., London, 1950.

60. Wilson R. H., Georg A., Nitz P., "Switchable glazing with a large dynamic range in total solar energy transmittance (g value)", World Renewable Energy Congress VI, Oxford, 2000.

APPENDIX A:

SOLAR GEOMETRY-CALCULATION OF THE SOLAR INCIDENCE ANGLE (Mathcad 2000 program)

This quicksheet calculates the angle of incidence as a function of solar time (t) and day number (m).

The angle of incidence is the angle between the solar rays and a line normal to the surface.

Latitude: $L := 44 \cdot deg$ Local standard time meridian: $STM := 75 \cdot deg$

Longitude: $LNG := 74 \cdot deg$ Window surface azimuth: $\psi := -10 \cdot deg$

Day number of year: n **Local standard time: t**

Equation of time:

$$ET(n) := \left(9.87 \cdot \sin\left(4 \cdot \pi \cdot \frac{n-81}{364}\right) - 7.53 \cdot \cos\left(2 \cdot \pi \cdot \frac{n-81}{364}\right) - 1.5 \cdot \sin\left(2 \cdot \pi \cdot \frac{n-81}{364}\right)\right) \cdot min$$

Apparent Solar Time: $AST(n,t) := t \cdot hr + ET(n) + \frac{(STM - LNG) \cdot hr}{15 \cdot deg}$

Solar declination: $\delta(n) := 23.45 \cdot deg \cdot \sin\left(360 \cdot \frac{284+n}{365} \cdot deg\right)$

Hour angle: $H(n,t) := (AST(n,t) - 12 \cdot hr) \cdot \left(15 \cdot \frac{deg}{hr}\right)$

Solar altitude:

$$\alpha(n,t) := if\left(asin\left(\cos(L) \cdot \cos(\delta(n)) \cdot \cos(H(n,t)) \ldots + \sin(L) \cdot \sin(\delta(n))\right) > 0 \cdot deg, asin\left(\cos(L) \cdot \cos(\delta(n)) \cdot \cos(H(n,t)) \ldots + \sin(L) \cdot \sin(\delta(n))\right), 0 \cdot deg\right)$$

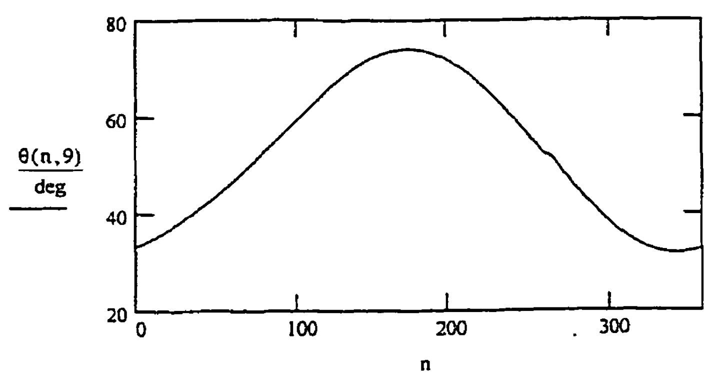
Solar azimuth: $\phi(n,t) := acos\left(\frac{\sin(\alpha(n,t)) \cdot \sin(L) - \sin(\delta(n))}{\cos(\alpha(n,t)) \cdot \cos(L)}\right) \cdot \frac{H(n,t)}{|H(n,t)|}$

Surface solar azimuth: $\gamma(n,t) := \phi(n,t) - \psi$

The surface tilt angle of the window is 90 degrees. The angle of incidence, is:

$$\theta\theta(n,t) := \cos(\alpha(n,t)) \cdot \cos(|\gamma(n,t)|)$$

$$\theta(n,t) := acos\left(\frac{\theta\theta(n,t) + |\theta\theta(n,t)|}{2}\right)$$ .. angle of incidence

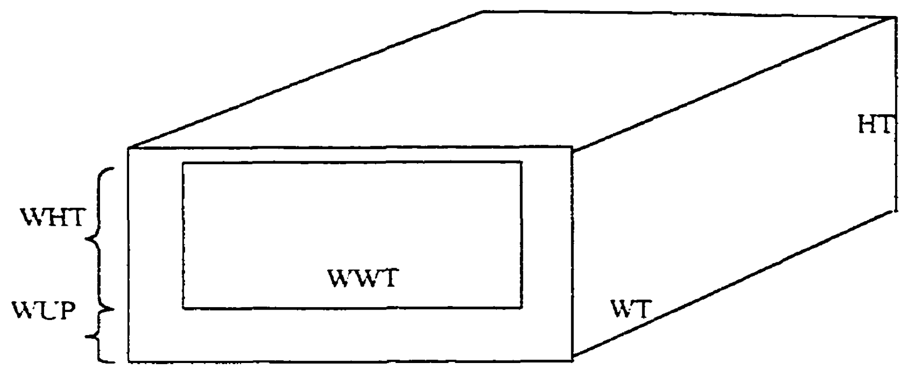


APPENDIX B:

FORM FACTORS CALCULATION
(Mathcad 2000 program)

This quicksheet calculates the form factors between all interior surfaces of a rectangular room with one window.

Consider an office space (rectangular) with the following dimensions and properties.



Room dimensions:

height $HT := 3 \cdot m$

width $WT := 5 \cdot m$

length $LT := 5 \cdot m$

window length $WWT := 4 \cdot m$

window height $WHT := 2 \cdot m$

distance from window to floor $WUP := 0.8 \cdot m$ (work − planeheight)

distance from window to ceiling $WCE := HT - WHT - WUP$ $WCE = 0.2\,m$

distance from window to walls $WWW := \frac{LT - WWT}{2}$

Total number of interior surfaces: $n := 7$

Surfaces indices: $i := 1..n$ $j := 1..n$

1. Window
2. Wall containing the window
3. Floor
4. Ceiling
5. Back wall
6. Right wall
7. Left wall

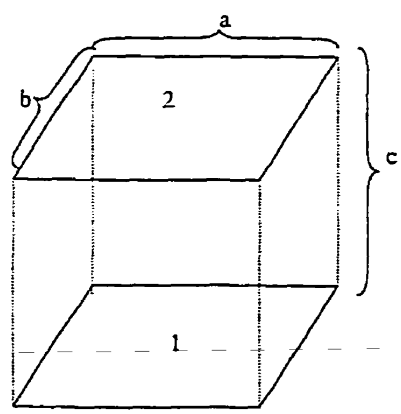
Surface areas:

$A1 := WWT \cdot WHT \quad A2 := LT \cdot HT - A1 \quad A3 := LT \cdot WT \quad A4 := A3 \quad A5 := LT \cdot HT$

$A6 := WT \cdot HT \qquad A7 := A6$

CALCULATION OF VIEW FACTORS BETWEEN ALL SURFACES, Fij

The view factor between two identical, directly opposed rectangles is:

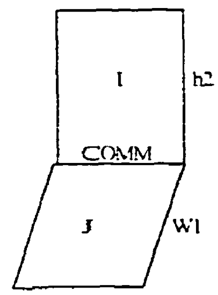


$$x = \frac{a}{c}$$

$$y = \frac{b}{c}$$

$$Fij(x,y) := \frac{2}{\pi \cdot x \cdot y} \cdot \left[\ln\left[\sqrt{\frac{(1+x^2)\cdot(1+y^2)}{1+x^2+y^2}} \right] + x \cdot \sqrt{1+y^2} \cdot \mathrm{atan}\left(\frac{x}{\sqrt{1+y^2}} \right) + y \cdot \sqrt{1+x^2} \cdot \mathrm{atan}\left(\frac{y}{\sqrt{1+x^2}} \right) - x \cdot at \right.$$

The view factor between two finite rectangles of the same length, having one common edge, and at angle of 90 degrees to each other, is:



$$w = \frac{w1}{comm} \qquad h = \frac{h2}{comm}$$

$$A(h,w) := h^2 + w^2 \qquad B(w) := 1 + w^2 \qquad C(h) := 1 + h^2$$

$$D(h,w) := 1 - \left(h^2 - w^2\right) \qquad E(w) := w^2 \qquad G(h) := h^2$$

View factor Fij from i to j:

$$F12(w,h) := \frac{\left(w \cdot atan\left(\frac{1.}{w}\right) + h \cdot atan\left(\frac{1}{h}\right)\right) - \sqrt{A(h,w)} \cdot atan\left(\frac{1}{\sqrt{A(h,w)}}\right) \dots + 0.25 \cdot \ln\left[\left(\frac{E(w) \cdot D(h,w)}{B(w) \cdot A(h,w)}\right)^{E(w)} \cdot \left(\frac{G(h) \cdot D(h,w)}{C(h) \cdot A(h,w)}\right)^{G(h)} \cdot \frac{B(w) \cdot C(h)}{D(h,w)}\right]}{\pi \cdot w}$$

The other view factors between the room surfaces are calculated by applying the following principles:

1. Reciprocity: $A_i \cdot F_{i,j} = A_j \cdot F_{j,i}$

2. Symmetry, e.g. $F_{4,6} = F_{4,7}$

3. Energy conservation: $\sum_j F_{i,j} = 1$ (for any surface i)

$F_{1,1} := 0$ $F_{2,2} := 0$ $F_{3,3} := 0$ $F_{4,4} := 0$ $F_{5,5} := 0$ $F_{6,6} := 0$ $F_{7,7} := 0$

VIEW FACTORS BETWEEN FLOOR AND CEILING:

$a := LT$ $b := WT$ $c := HT$ $x := \frac{a}{c}$ $y := \frac{b}{c}$

$F_{3,4} := Fij(x,y)$ $F_{3,4} = 0.354$ $F_{4,3} := F_{3,4}$

VIEW FACTORS BETWEEN RIGHT WALL AND LEFT WALL

$a := WT$ $b := HT$ $c := LT$ $x := \frac{a}{c}$ $y := \frac{b}{c}$

$F_{6,7} := Fij(x,y)$ $F_{6,7} = 0.136$ $F_{7,6} := F_{6,7}$

VIEW FACTORS BETWEEN FLOOR AND BACK WALL AND CEILING AND BACK WALL

$w1 := WT$ $h2 := HT$ $comm := LT$ $w := \frac{w1}{comm}$ $h := \frac{h2}{comm}$

$F_{3,5} := F12(w,h)$ $F_{3,5} = 0.161$ $F_{5,3} := \frac{F_{3,5}}{A5} \cdot A3$ $F_{5,3} = 0.269$

$F_{4,5} := F_{3,5}$ $F_{5,4} := F_{5,3}$ ... from symmetry

VIEW FACTORS BETWEEN BACK WALL AND RIGHT/LEFT WALL

$w1 := LT$ $h2 := WT$ $comm := HT$ $w := \frac{w1}{comm}$ $h := \frac{h2}{comm}$

$F_{5,6} := F12(w,h)$ $F_{5,6} = 0.163$ $F_{5,7} := F_{5,6}$ $F_{6,5} := \frac{A5}{A6} \cdot F_{5,6}$ $F_{6,5} = 0.163$ $F_{7,5} := F_{6,5}$

VIEW FACTORS BETWEEN FLOOR AND RIGHT/LEFT WALL AND CEILING AND RIGHT/LEFT WALL

$w1 := LT \quad h2 := HT \quad comm := WT \quad w := \frac{w1}{comm} \quad h := \frac{h2}{comm}$

$F_{3,6} := F12(w,h) \quad F_{3,6} = 0.161 \quad F_{3,7} := F_{3,6} \quad F_{6,3} := \frac{A3}{A6} \cdot F_{3,6} \quad F_{7,3} := F_{6,3}$

$F_{4,6} := F_{3,6} \quad F_{4,7} := F_{3,7} \quad F_{6,4} := F_{6,3} \quad F_{7,4} := F_{7,3}$ ... from symmetry

$F_{6,3} = 0.269 \quad F_{7,3} = 0.269$

VIEW FACTORS BETWEEN WINDOW AND FLOOR

Now we have to separate the floor in 3 parts and the window wall in 5 parts.

$Ab := 20 \cdot m^2 \quad Ad := 3.2 \cdot m^2 \quad A2 := 8 \cdot m^2 \quad Ac1 := 1 \cdot m^2 \quad Ac2 := 0.4 \cdot m^2 \quad Aa := 2.5 \cdot m^2$

$Aab := 22.5 \cdot m^2$

$w1 := WT \quad h2 := 2.8 \cdot m \quad comm := 4 \cdot m \quad w := \frac{w1}{comm} \quad h := \frac{h2}{comm}$

$Fb2d := F12(w,h) \quad Fb2d = 0.146$

$w1 := WT \quad h2 := 0.8 \cdot m \quad comm := 4 \cdot m \quad w := \frac{w1}{comm} \quad h := \frac{h2}{comm}$

$Fbd := F12(w,h) \quad Fbd = 0.063$

$w1 := WT \quad h2 := 0.8 \cdot m \quad comm := 0.5 \cdot m \quad w := \frac{w1}{comm} \quad h := \frac{h2}{comm}$

$Fac2 := F12(w,h) \quad Fac2 = 0.032$

$w1 := WT \quad h2 := 2.8 \cdot m \quad comm := 0.5 \cdot m \quad w := \frac{w1}{comm} \quad h := \frac{h2}{comm}$

$Fac1c2 := F12(w,h) \quad Fac1c2 = 0.049$

$w1 := WT \quad h2 := 2.8 \cdot m \quad comm := 4.5 \cdot m \quad w := \frac{w1}{comm} \quad h := \frac{h2}{comm}$

$Fabc1c2d2 := F12(w,h) \quad Fabc1c2d2 = 0.151$

$wl := WT \qquad h2 := 0.8\cdot m \qquad comm := 4.5\cdot m \qquad w := \frac{wl}{comm} \qquad h := \frac{h2}{comm}$

$Fabc2d := F12(w,h) \qquad Fabc2d = 0.064$

$Fb2 := Fb2d - Fbd \qquad Fb2 = 0.083 \qquad F2b := \frac{Ab}{A2}\cdot Fb2$

$$Fa2d := \frac{Aab\cdot Fabc1c2d2 - Aa\cdot Fac1c2 - Ab\cdot Fb2d}{2\cdot Aa} \qquad Fa2d = 0.072$$

$$Fad := \frac{Aab\cdot Fabc2d - Aa\cdot Fac2 - Ab\cdot Fbd}{2\cdot Aa} \qquad Fad = 0.02$$

$Fa2 := Fa2d - Fad \qquad Fa2 = 0.052 \qquad F2a := \frac{Aa}{A2}\cdot Fa2 \qquad F2a = 0.016$

$F_{1,3} := 2\cdot F2a + F2b \qquad F_{1,3} = 0.24 \qquad F_{3,1} := \frac{A1}{A3}\cdot F_{1,3} \qquad F_{3,1} = 0.077$

<u>VIEW FACTORS BETWEEN WINDOW AND CEILING</u>

This view factor would be equal to the one between the window and the floor, if the window was placed in the middle of the wall.

$Ab := 20\cdot m^2 \qquad Ad := 0.8\cdot m^2 \qquad A2 := 8\cdot m^2 \qquad Ac1 := 1\cdot m^2 \qquad Ac2 := 0.1\cdot m^2 \qquad Aa := 2.5\cdot m^2$

$Aab := 22.5\cdot m^2$

$wl := WT \qquad h2 := 2.2\cdot m \qquad comm := 4\cdot m \qquad w := \frac{wl}{comm} \qquad h := \frac{h2}{comm}$

$Fb2d := F12(w,h) \qquad Fb2d = 0.128$

$wl := WT \qquad h2 := 0.2\cdot m \qquad comm := 4\cdot m \qquad w := \frac{wl}{comm} \qquad h := \frac{h2}{comm}$

$Fbd := F12(w,h) \qquad Fbd = 0.018$

$wl := WT \qquad h2 := 0.2\cdot m \qquad comm := 0.5\cdot m \qquad w := \frac{wl}{comm} \qquad h := \frac{h2}{comm}$

$Fac2 := F12(w,h) \qquad Fac2 = 0.014$

$wl := WT \qquad h2 := 2.2\cdot m \qquad comm := 0.5\cdot m \qquad w := \frac{wl}{comm} \qquad h := \frac{h2}{comm}$

$Fac1c2 := F12(w,h) \qquad Fac1c2 = 0.046$

$w1 := WT \qquad h2 := 2.2\cdot m \qquad comm := 4.5\cdot m \qquad w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$

$Fabc1c2d2 := F12(w,h) \qquad Fabc1c2d2 = 0.132$

$w1 := WT \qquad h2 := 0.2\cdot m \qquad comm := 4.5\cdot m \qquad w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$

$Fabc2d := F12(w,h) \qquad Fabc2d = 0.019$

$Fb2 := Fb2d - Fbd \qquad Fb2 = 0.109 \qquad F2b := \frac{Ab}{A2}\cdot Fb2$

$$Fa2d := \frac{Aab\cdot Fabc1c2d2 - Aa\cdot Fac1c2 - Ab\cdot Fb2d}{2\cdot Aa} \qquad Fa2d = 0.059$$

$$Fad := \frac{Aab\cdot Fabc2d - Aa\cdot Fac2 - Ab\cdot Fbd}{2\cdot Aa} \qquad Fad = 2.86 \times 10^{-3}$$

$Fa2 := Fa2d - Fad \qquad Fa2 = 0.057 \qquad F2a := \frac{Aa}{A2}\cdot Fa2 \qquad F2a = 0.018$

$F_{1,4} := 2\cdot F2a + F2b \qquad F_{1,4} = 0.309 \qquad F_{4,1} := \frac{A1}{A3}\cdot F_{1,4} \qquad F_{4,1} = 0.099$

VIEW FACTORS BETWEEN WINDOW AND RIGHT/LEFT WALLS

The view factors between the window and the left wall and between the window and the right wall will be equal because of symmetry.

PART CLOSE TO FLOOR

$Ab := 10\cdot m^2 \quad Ad := 1\cdot m^2 \quad A2 := 8\cdot m^2 \quad Ac1 := 3.2\cdot m^2 \quad Ac2 := 0.4\cdot m^2 \quad Aa := 4\cdot m^2 \quad Aab := 14\cdot m^2$

$w1 := WT \qquad h2 := 4.5\cdot m \qquad comm := 2\cdot m \qquad w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$

$Fb2d := F12(w,h) \qquad Fb2d = 0.13$

$w1 := WT \qquad h2 := 0.5\cdot m \qquad comm := 2\cdot m \qquad w := \frac{w1}{comm} \qquad h := \frac{h2}{comm}$

$Fbd := F12(w,h) \qquad Fbd = 0.038$

$wl := WT \quad h2 := 0.5 \cdot m \quad comm := 0.8 \cdot m \quad w := \frac{wl}{comm} \quad h := \frac{h2}{comm}$

$Fac2 := F12(w,h) \quad Fac2 = 0.03$

$wl := WT \quad h2 := 4.5 \cdot m \quad comm := 0.8 \cdot m \quad w := \frac{wl}{comm} \quad h := \frac{h2}{comm}$

$Fac1c2 := F12(w,h) \quad Fac1c2 = 0.075$

$wl := WT \quad h2 := 4.5 \cdot m \quad comm := 2.8 \cdot m \quad w := \frac{wl}{comm} \quad h := \frac{h2}{comm}$

$Fabc1c2d2 := F12(w,h) \quad Fabc1c2d2 = 0.153$

$wl := WT \quad h2 := 0.5 \cdot m \quad comm := 2.8 \cdot m \quad w := \frac{wl}{comm} \quad h := \frac{h2}{comm}$

$Fabc2d := F12(w,h) \quad Fabc2d = 0.04$

$Fb2 := Fb2d - Fbd \quad Fb2 = 0.091 \quad F2b := \frac{Ab}{A2} \cdot Fb2$ (I)

$Fa2d := \frac{Aab \cdot Fabc1c2d2 - Aa \cdot Fac1c2 - Ab \cdot Fb2d}{2 \cdot Aa} \quad Fa2d = 0.069$

$Fad := \frac{Aab \cdot Fabc2d - Aa \cdot Fac2 - Ab \cdot Fbd}{2 \cdot Aa} \quad Fad = 7.997 \times 10^{-3}$

$Fa2 := Fa2d - Fad \quad Fa2 = 0.061 \quad F2a := \frac{Aa}{A2} \cdot Fa2 \quad F2a = 0.03$ (II)

PART CLOSE TO CEILING

$Ab := 10 \cdot m^2 \quad Ad := 1 \cdot m^2 \; A2 := 8 \cdot m^2 \quad Ac1 := 0.8 \cdot m^2 \quad Ac2 := 0.1 \cdot m^2 \quad Aa := 1 \cdot m^2 \quad Aab := 11 \cdot m^2$

$wl := WT \quad h2 := 4.5 \cdot m \quad comm := 2 \cdot m \quad w := \frac{wl}{comm} \quad h := \frac{h2}{comm}$

$Fb2d := F12(w,h) \quad Fb2d = 0.13$

$wl := WT \quad h2 := 0.5 \cdot m \quad comm := 2 \cdot m \quad w := \frac{wl}{comm} \quad h := \frac{h2}{comm}$

$Fbd := F12(w,h) \quad Fbd = 0.038$

$wl := WT \quad h2 := 0.5 \cdot m \quad comm := 0.2 \cdot m \quad w := \frac{wl}{comm} \quad h := \frac{h2}{comm}$

$Fac2 := F12(w,h)$ $Fac2 = 0.015$

$wl := WT$ $h2 := 4.5 \cdot m$ $comm := 0.2 \cdot m$ $w := \frac{wl}{comm}$ $h := \frac{h2}{comm}$

$Fac1c2 := F12(w,h)$ $Fac1c2 = 0.027$

$wl := WT$ $h2 := 4.5 \cdot m$ $comm := 2.2 \cdot m$ $w := \frac{wl}{comm}$ $h := \frac{h2}{comm}$

$Fabc1c2d2 := F12(w,h)$ $Fabc1c2d2 = 0.136$

$wl := WT$ $h2 := 0.5 \cdot m$ $comm := 2.2 \cdot m$ $w := \frac{wl}{comm}$ $h := \frac{h2}{comm}$

$Fabc2d := F12(w,h)$ $Fabc2d = 0.039$

$Fb2 := Fb2d - Fbd$ $Fb2 = 0.091$ $F2b := \frac{Ab}{A2} \cdot Fb2$ $F2b = 0.114$ (I)

$$Fa2d := \frac{Aab \cdot Fabc1c2d2 - Aa \cdot Fac1c2 - Ab \cdot Fb2d}{2 \cdot Aa} \qquad Fa2d = 0.087$$

$$Fad := \frac{Aab \cdot Fabc2d - Aa \cdot Fac2 - Ab \cdot Fbd}{2 \cdot Aa} \qquad Fad = 0.015$$

$Fa2 := Fa2d - Fad$ $Fa2 = 0.072$ $F2a := \frac{Aa}{A2} \cdot Fa2$ $F2a = 9.026 \times 10^{-3}$ (III)

So $F_{1,6} := 0.114 + 0.009026 + 0.03$ $F_{1,6} = 0.153$ $F_{6,1} := \frac{A1}{A6} \cdot F_{1,6}$ $F_{6,1} = 0.082$

and $F_{1,7} := F_{1,6}$ $F_{7,1} := F_{6,1}$ Also $F_{1,2} := 0$ $F_{2,1} := 0$ (on the same wall)

VIEW FACTOR FROM WINDOW TO BACK WALL

The sum of the view factors between the window and all surfaces must be equal to 1. Since we know all the other view factors, it will be:

$$F_{1,5} := 1 - F_{1,2} - F_{1,3} - F_{1,4} - F_{1,5} - F_{1,6} - F_{1,7}$$

$F_{1,5} = 0.145$ and $F_{5,1} := \frac{A1}{A5} \cdot F_{1,5}$ $F_{5,1} = 0.077$

OTHER VIEW FACTORS

Now it remains to calculate the view factors between the wall containing the window and all the other surfaces. We will find these view factors from the energy conservation equation. Since the sum of the view factors between a surface and all the others is equal to 1, it is:

$$F_{i,2} = 1 - F_{i,1} - F_{i,3} - F_{i,4} - F_{i,5} - F_{i,6} - F_{i,7}$$

and we find:

$F_{1,2} := 0 \quad F_{2,2} := 0 \quad F_{3,2} := 0.086 \quad F_{4,2} := 0.064 \quad F_{5,2} := 0.059 \quad F_{6,2} := 0.081 \quad F_{7,2} := 0.081$

$F_{2,1} := 0 \qquad F_{2,2} := 0 \qquad F_{2,3} := \frac{A3}{A2} \cdot F_{3,2} \qquad F_{2,4} := \frac{A4}{A2} \cdot F_{4,2} \qquad F_{2,5} := \frac{A5}{A2} \cdot F_{5,2}$

$F_{2,6} := \frac{1 - F_{2,3} - F_{2,4} - F_{2,5}}{2} \qquad F_{2,7} := F_{2,6}$

The view factors in matrix form, are:

$$F = \begin{pmatrix} 0 & 0 & 0.24 & 0.309 & 0.145 & 0.153 & 0.153 \\ 0 & 0 & 0.269 & 0.2 & 0.111 & 0.21 & 0.21 \\ 0.077 & 0.086 & 0 & 0.354 & 0.161 & 0.161 & 0.161 \\ 0.099 & 0.064 & 0.354 & 0 & 0.161 & 0.161 & 0.161 \\ 0.077 & 0.059 & 0.269 & 0.269 & 0 & 0.163 & 0.163 \\ 0.082 & 0.081 & 0.269 & 0.269 & 0.163 & 0 & 0.136 \\ 0.082 & 0.081 & 0.269 & 0.269 & 0.163 & 0.136 & 0 \end{pmatrix}$$

The sum of each row must be equal to 1 (energy conservation)

APPENDIX C:

CONFIGURATION FACTORS CALCULATION
(Mathcad 2000 program)

This quicksheet calculates the configuration factors between four points on the work plane and all the interior surfaces of the room.

COORDINATES OF THE POINTS

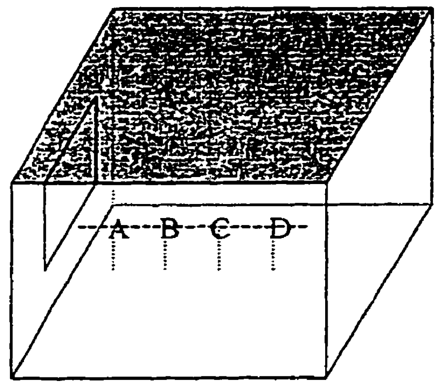
Consider 4 points A,B,C,D in the room, at the work-plane height, 2.5m from the left and right wall. The coordinates of each point are:

A(0.94,2.5,0.8)

B(1.88,2.5,0.8)

C(2.82,2.5,0.8)

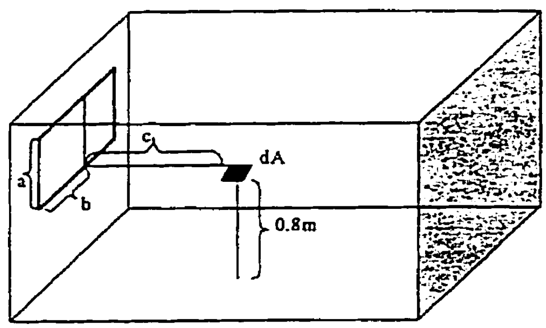
D(3.76,2.5,0.8)



$i := 1..7$ (surface index)

CALCULATION OF CONFIGURATION FACTORS BETWEEN POINTS A,B,C,D AND ALL INTERIOR SURFACES

Consider a differential area dA (point) as in the figure below. To calculate the configuration factors between dA and e.g. the window, we separate the window in two parts and calculate each configuration factor separately.



$a = y \qquad b = x \qquad c = z$

The configuration factor between a surface and a point is:

$$f(x,y,z) := \frac{1}{2\cdot\pi}\cdot\left(\operatorname{atan}\left(\frac{x}{z}\right) - \frac{z}{\sqrt{y^2+z^2}}\cdot\operatorname{atan}\left(\frac{x}{\sqrt{y^2+z^2}}\right)\right)$$

CONFIGURATION FACTORS BETWEEN WINDOW AND POINTS A,B,C,D

$x := 2 \qquad y := 2 \qquad z := 0.94 \qquad f_{A_1} := 2\,f(x,y,z) \qquad f_{A_1} = 0.261$

$x := 2 \qquad y := 2 \qquad z := 1.88 \qquad f_{B_1} := 2\cdot f(x,y,z) \qquad f_{B_1} = 0.123$

$x := 2 \qquad y := 2 \qquad z := 2.82 \qquad f_{C_1} := 2\cdot f(x,y,z) \qquad f_{C_1} = 0.06$

$x := 2 \qquad y := 2 \qquad z := 3.76 \qquad f_{D_1} := 2\cdot f(x,y,z) \qquad f_{D_1} = 0.032$

CONFIGURATION FACTORS BETWEEN A,B,C,D AND CEILING

Now dA is parallel to the surface, so we will use the equation:

$$f(x,y,z) := \frac{1}{2\cdot\pi}\cdot\left[\left(\frac{y}{\sqrt{y^2+z^2}}\right)\cdot \mathrm{atan}\left(\frac{x}{\sqrt{y^2+z^2}}\right) + \frac{x}{\sqrt{x^2+z^2}}\cdot \mathrm{atan}\left(\frac{y}{\sqrt{x^2+z^2}}\right)\right]$$

$x := 0.94$ $y := 2.5$ $z := 2.2$ $f_{A1_4} := f(x,y,z)$ $f_{A1_4} = 0.083$

$x := 4.06$ $y := 2.5$ $z := 2.2$ $f_{A2_4} := f(x,y,z)$ $f_{A2_4} = 0.175$

$f_{A_4} := 2\cdot\left(f_{A1_4} + f_{A2_4}\right)$ $f_{A_4} = 0.517$

$x := 1.88$ $y := 2.5$ $z := 2.2$ $f_{B1_4} := f(x,y,z)$ $f_{B1_4} = 0.135$

$x := 3.12$ $y := 2.5$ $z := 2.2$ $f_{B2_4} := f(x,y,z)$ $f_{B2_4} = 0.165$

$f_{B_4} := 2\cdot\left(f_{B1_4} + f_{B2_4}\right)$ $f_{B_4} = 0.601$

$x := 2.82$ $y := 2.5$ $z := 2.2$ $f_{C1_4} := f(x,y,z)$ $f_{C1_4} = 0.161$

$x := 2.18$ $y := 2.5$ $z := 2.2$ $f_{C2_4} := f(x,y,z)$ $f_{C2_4} = 0.145$

$f_{C_4} := 2\cdot\left(f_{C1_4} + f_{C2_4}\right)$ $f_{C_4} = 0.612$

$x := 3.76$ $y := 2.5$ $z := 2.2$ $f_{D1_4} := f(x,y,z)$ $f_{D1_4} = 0.173$

$x := 1.24$ $y := 2.5$ $z := 2.2$ $f_{D2_4} := f(x,y,z)$ $f_{D2_4} = 0.104$

$f_{D_4} := 2\cdot\left(f_{D1_4} + f_{D2_4}\right)$ $f_{D_4} = 0.552$

CONFIGURATION FACTORS BETWEEN A,B,C,D AND CEILING

Now dA is parallel to the surface, so we will use the equation:

$$f(x,y,z) := \frac{1}{2\cdot\pi}\cdot\left[\left(\frac{y}{\sqrt{y^2+z^2}}\right)\cdot\operatorname{atan}\left(\frac{x}{\sqrt{y^2+z^2}}\right)+\frac{x}{\sqrt{x^2+z^2}}\cdot\operatorname{atan}\left(\frac{y}{\sqrt{x^2+z^2}}\right)\right]$$

$x := 0.94 \quad y := 2.5 \quad z := 2.2 \quad f_{A1_4} := f(x,y,z) \quad f_{A1_4} = 0.083$

$x := 4.06 \quad y := 2.5 \quad z := 2.2 \quad f_{A2_4} := f(x,y,z) \quad f_{A2_4} = 0.175$

$f_{A_4} := 2\cdot\left(f_{A1_4} + f_{A2_4}\right) \quad f_{A_4} = 0.517$

$x := 1.88 \quad y := 2.5 \quad z := 2.2 \quad f_{B1_4} := f(x,y,z) \quad f_{B1_4} = 0.135$

$x := 3.12 \quad y := 2.5 \quad z := 2.2 \quad f_{B2_4} := f(x,y,z) \quad f_{B2_4} = 0.165$

$f_{B_4} := 2\cdot\left(f_{B1_4} + f_{B2_4}\right) \quad f_{B_4} = 0.601$

$x := 2.82 \quad y := 2.5 \quad z := 2.2 \quad f_{C1_4} := f(x,y,z) \quad f_{C1_4} = 0.161$

$x := 2.18 \quad y := 2.5 \quad z := 2.2 \quad f_{C2_4} := f(x,y,z) \quad f_{C2_4} = 0.145$

$f_{C_4} := 2\cdot\left(f_{C1_4} + f_{C2_4}\right) \quad f_{C_4} = 0.612$

$x := 3.76 \quad y := 2.5 \quad z := 2.2 \quad f_{D1_4} := f(x,y,z) \quad f_{D1_4} = 0.173$

$x := 1.24 \quad y := 2.5 \quad z := 2.2 \quad f_{D2_4} := f(x,y,z) \quad f_{D2_4} = 0.104$

$f_{D_4} := 2\cdot\left(f_{D1_4} + f_{D2_4}\right) \quad f_{D_4} = 0.552$

Since dA does not see the floor (we are interested in horizontal illuminance coming from upwards), it is :

$f_{A_3} := 0 \qquad f_{B_3} := 0 \qquad f_{C_3} := 0 \qquad f_{D_3} := 0$

It remains to calculate the configuration factors between the wall containing the window and A,B,C,D. These will be again calculated from the energy conservation equation:

$$f_{A_2} := 1 - f_{A_1} - f_{A_3} - f_{A_4} - f_{A_5} - f_{A_6} - f_{A_7} \qquad f_{A_2} = 0.024$$

$$f_{B_2} := 1 - f_{B_1} - f_{B_3} - f_{B_4} - f_{B_5} - f_{B_6} - f_{B_7} \qquad f_{B_2} = 0.025$$

$$f_{C_2} := 1 - f_{C_1} - f_{C_3} - f_{C_4} - f_{C_5} - f_{C_6} - f_{C_7} \qquad f_{C_2} = 0.018$$

$$f_{D_2} := 1 - f_{D_1} - f_{D_3} - f_{D_4} - f_{D_5} - f_{D_6} - f_{D_7} \qquad f_{D_2} = 0.011$$

$f_{A_i} =$	$f_{B_i} =$	$f_{C_i} =$	$f_{D_i} =$
0.261	0.123	0.06	0.032
0.024	0.025	0.018	0.011
0	0	0	0
0.517	0.601	0.612	0.552
0.037	0.064	0.12	0.231
0.081	0.094	0.095	0.086
0.081	0.094	0.095	0.086

APPENDIX D:

ILLUMINANCE LEVEL AND LIGHT DIMMING FACTORS CALCULATIONS ON OVERCAST DAYS (Mathcad 2000 program)

This quicksheet calculates the illuminance on each of the four points A,B,C and D as a function of solat time and day number on overcast days.

DAYLIGHT INCIDENT ON WINDOW

The horizontal illuminance under a CIE overcast sky may be calculated from the formula:

$$E_h(n,t) := 1000\cdot(0.3 + 21\cdot\sin(\alpha(n,t)))\cdot lx$$

The illuminance incident on the window from the sky (since there is only diffuse light), will be equal to the horizontal illuminance multiplied by the view factor between the window and the sky, which is assumed 0.5 (window sees half of the sky):

$$E_{wsky}(n,t) := E_h(n,t)\cdot 0.5$$

There is also incident daylight on the window coming from the ground. This is equal to the horizontal illuminance (on the ground) multiplied by the ground reflectance and the view factor between the window and the ground (which is also assumed 0.5) :

$\rho_{gr} := 0.2$ .. ground reflectance

$$E_{wgr}(n,t) := E_h(n,t)\cdot\rho_{gr}\cdot 0.5$$

The total illuminance incident on the window is equal to the sum of these two compartments:

$$E_w(n,t) := E_{wsky}(n,t) + E_{wgr}(n,t)$$

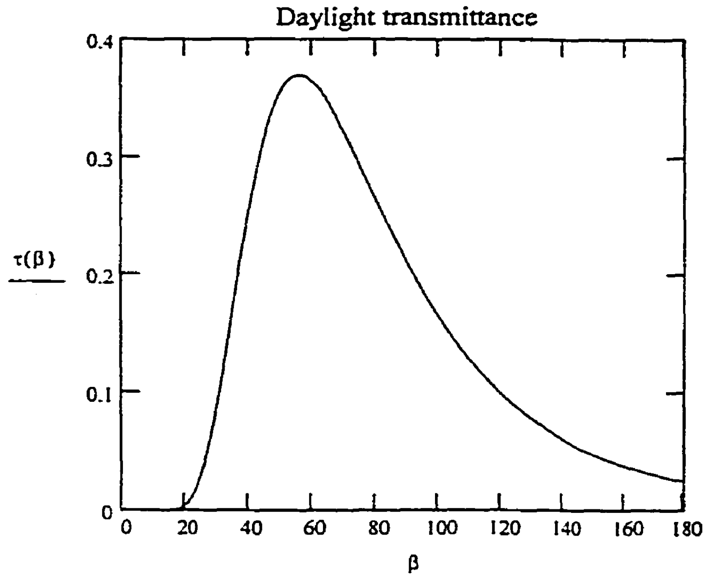
$$E_w(n,t) := 500\cdot(0.3 + 21\cdot\sin(\alpha(n,t)))\cdot(1 + \rho_{gr})\cdot lx$$

DAYLIGHT TRANSMITTED THROUGH THE WINDOW

The daylight transmittance under overcast conditions, is only a function of blinds tilt angle,β (the effect of angle of incidence is negligible in this case):

$\beta := 1,2..180$ ...blind tilt angle

$$\tau(\beta) := \frac{4.5\cdot 10^{12}\cdot\beta^{-6}}{e^{\frac{335}{\beta}} - 1}$$ ...daylight transmittance for overcast sky



The maximum amount of daylight is transmitted for blind tilt angles near 65 degrees. In order to combine with maximum view outside, we will set the blinds at 75 degrees tilt angle.

$E_t(n,t) := E_w(n,t)\cdot\tau(75)$ ... Daylight transmitted through the window for 75 degrees blinds tilt angle

LUMINOUS EXITANCE OF ALL INTERIOR SURFACES

Now the office space is consdered as an enclosure with only one luminous source (the window) which emits diffuse light uniformily towards all directions (surfaces). The final luminous exitance of each surface will now be calculated after multiple reflections on every room interior surfaces. First, we represent the initial luminous exitances of the room interior surfaces in matrix form:

Matrix of initial luminous exitances:

$$M_o(n,t) := \begin{pmatrix} E_t(n,t) \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

View factors matrix:

$$F = \begin{pmatrix} 0 & 0 & 0.24 & 0.309 & 0.145 & 0.153 & 0.153 \\ 0 & 0 & 0.269 & 0.2 & 0.111 & 0.21 & 0.21 \\ 0.077 & 0.086 & 0 & 0.354 & 0.161 & 0.161 & 0.161 \\ 0.099 & 0.064 & 0.354 & 0 & 0.161 & 0.161 & 0.161 \\ 0.077 & 0.059 & 0.269 & 0.269 & 0 & 0.163 & 0.163 \\ 0.082 & 0.081 & 0.269 & 0.269 & 0.163 & 0 & 0.136 \\ 0.082 & 0.081 & 0.269 & 0.269 & 0.163 & 0.136 & 0 \end{pmatrix}$$

Surfaces reflectance matrix:

$$\rho := \begin{pmatrix} 0.1 \\ 0.7 \\ 0.3 \\ 0.8 \\ 0.7 \\ 0.7 \\ 0.7 \end{pmatrix} \quad \begin{pmatrix} \text{Window} \\ \text{"Wall containing window"} \\ \text{Floor} \\ \text{Ceiling} \\ \text{"Back wall"} \\ \text{"Right wall"} \\ \text{"Left wall"} \end{pmatrix}$$

The final illuminance of each interior surface after multiple reflections, can be calculated from the formula:

$$M_i = M_{o_i} + \rho_i \cdot \sum_{i=1}^{n} M_j \cdot F_{i,j}$$

Solving for the initial illuminances, it is:

$$M_{o_i} = M_i - \rho_i \cdot \sum_{i=1}^{n} M_j \cdot F_{i,j}$$ or, analytically:

$$M_{o_1} = M_1 - (\rho_1 \cdot M_1 \cdot F_{1,1} + ... + \rho_1 \cdot M_7 \cdot F_{1,7})$$

$$M_{o_2} = M_2 - (\rho_2 \cdot M_1 \cdot F_{2,1} + ... + \rho_2 \cdot M_7 \cdot F_{2,7})$$

....

$$M_{o_7} = M_7 - (\rho_7 \cdot M_1 \cdot F_{7,1} + ... + \rho_7 \cdot M_7 \cdot F_{7,7})$$

This system can be written in matrix form:

$$M_o = (I - TT) \cdot M$$

where I is the 7x7 identity matrix and TT is a matrix each element of which is equal to:

$$TT_{i,j} = \rho_i \cdot F_{i,j}$$

Once matrix TT is calculated, the final luminous exitance of each surface will be:

$$M_i = (I - TT)^{-1} \cdot M_{o_i}$$

$TT_{i,j} := \rho_i \cdot F_{i,j}$ $\qquad$ $I := \text{identity}(7)$

$$TT = \begin{pmatrix} 0 & 0 & 0.024 & 0.031 & 0.014 & 0.015 & 0.015 \\ 0 & 0 & 0.188 & 0.14 & 0.077 & 0.147 & 0.147 \\ 0.023 & 0.026 & 0 & 0.106 & 0.048 & 0.048 & 0.048 \\ 0.079 & 0.051 & 0.284 & 0 & 0.129 & 0.129 & 0.129 \\ 0.054 & 0.041 & 0.188 & 0.188 & 0 & 0.114 & 0.114 \\ 0.057 & 0.057 & 0.188 & 0.188 & 0.114 & 0 & 0.095 \\ 0.057 & 0.057 & 0.188 & 0.188 & 0.114 & 0.095 & 0 \end{pmatrix}$$

FINAL LUMINOUS EXITANCES OF ALL SURFACES: $M(n,t) := (I - TT)^{-1} \cdot M_o(n,t)$

$$M(15,9) = \begin{pmatrix} 843.644 \\ 66.868 \\ 50.091 \\ 125.782 \\ 105.947 \\ 107.43 \\ 107.43 \end{pmatrix} \text{lx}$$

For overcast,
Day of year: 15 (Jan. 15),
Local Standard Time: 9 AM,
Blind tilt angle: 75 deg

$t := 9, 10..17$ ... new time index

ILLUMINANCE ON WORK PLANE

$$E_A(n,t) := \sum_{i=1}^{7} M(n,t)_i \cdot f_{A_i}$$

$$E_B(n,t) := \sum_{i=1}^{7} M(n,t)_i \cdot f_{B_i}$$

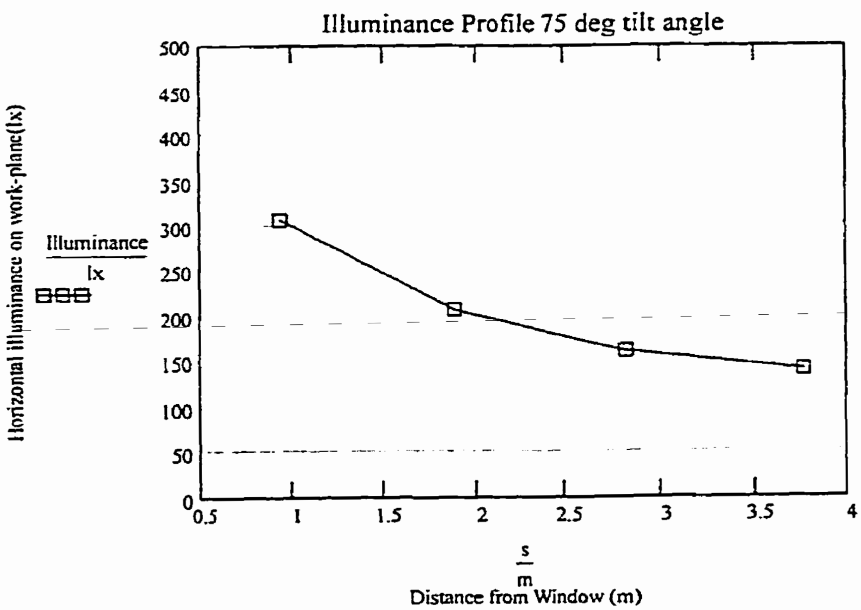
$$E_C(n,t) := \sum_{i=1}^{7} M(n,t)_i \cdot f_{C_i}$$

$$E_D(n,t) := \sum_{i=1}^{7} M(n,t)_i \cdot f_{D_i}$$

ILLUMINANCE PROFILE OF THE ROOM (9am, January 15th):

$Illuminance_i :=$ $\qquad s_i :=$ ... (distance from window)

Illuminance	s
$E_A(15,9)$	0.94
$E_B(15,9)$	1.88
$E_C(15,9)$	2.82
$E_D(15,9)$	3.76



This section calculates the light dimming factors for both luminaires as a function of day number and solar time, and the possible energy savings due to electric lighting on overcast days.

$t := 9, 10 .. 17$ ...Local Standard Time

$i := 1, 2 .. 12$ ... month number

$n_i := 30 \cdot i - 15$ ...Day Number of Year

$E_A(n_i, t) =$

	1
1	307.708
2	439.47
3	657.312
4	871.487
5	$1.005 \cdot 10^{3}$
6	$1.044 \cdot 10^{3}$

lx

This array contains all the illuminance values (for all days and times) on point A, in one column. It is more effective to have this array in 2D matrix form. The 12 columns represent the months (or days) and the rows the time of the day.

The same is done for points B, C and D :

$E_B(n_i, t) =$

	1
1	207.585
2	296.475
3	443.435
4	587.921
5	677.954
6	704.111

lx

$E_C(n_i, t) =$

	1
1	162.077
2	231.48
3	346.223
4	459.034
5	529.33
6	549.752

lx

$E_D(n_i, t) =$

	1
1	140.485
2	200.641
3	300.097
4	397.879
5	458.81
6	476.511

lx

$AA_{t,i} := E_A(n_i, t)$ $BB_{t,i} := E_B(n_i, t)$ $CC_{t,i} := E_C(n_i, t)$ $DD_{t,i} := E_D(n_i, t)$ ... 2D matrices

$AA =$

	1	2	3	4	5	6	7	8	9	10	11	12
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	307.7	439.5	657.3	871.5	$1 \cdot 10^{3}$	$1 \cdot 10^{3}$	$1 \cdot 10^{3}$	927.5	795.2	619.6	437.5	312.3
10	457.6	600.2	818.1	$1 \cdot 10^{3}$	$1.1 \cdot 10^{3}$	$1.2 \cdot 10^{3}$	$1.2 \cdot 10^{3}$	$1.1 \cdot 10^{3}$	943.4	757.5	568.9	447.9
11	554.1	706.2	921.7	$1.1 \cdot 10^{3}$	$1.2 \cdot 10^{3}$	$1.3 \cdot 10^{3}$	$1.3 \cdot 10^{3}$	$1.2 \cdot 10^{3}$	$1 \cdot 10^{3}$	835.5	642.7	529
12	590.8	750.1	961.1	$1.1 \cdot 10^{3}$	$1.3 \cdot 10^{3}$	$1.3 \cdot 10^{3}$	$1.3 \cdot 10^{3}$	$1.2 \cdot 10^{3}$	$1.1 \cdot 10^{3}$	848.4	653.9	549.9
13	565.1	729	933.6	$1.1 \cdot 10^{3}$	$1.2 \cdot 10^{3}$	$1.3 \cdot 10^{3}$	$1.3 \cdot 10^{3}$	$1.2 \cdot 10^{3}$	$1 \cdot 10^{3}$	795.3	601.7	509.2
14	478.7	644.4	841	$1 \cdot 10^{3}$	$1.1 \cdot 10^{3}$	$1.2 \cdot 10^{3}$	$1.2 \cdot 10^{3}$	$1.1 \cdot 10^{3}$	906.7	679.7	489.6	409.8
15	337.6	501.9	689.8	848.9	960.4	$1 \cdot 10^{3}$	$1 \cdot 10^{3}$	930.4	743.4	509.7	325.3	258.4
16	151.3	311.3	490.2	645.6	762.9	832.2	831.8	733.6	534.5	296.7	120.1	65.4
17	19.5	85.6	255.7	410.2	535.5	612.9	612.2	504.3	294.4	55.2	19.5	19.5

lx

Ve are only interested in the hours between 9am and 5pm, so we can extract the submatrix containing only these hours:

A := submatrix(AA, 9, 17, 1, 12) B := submatrix(BB, 9, 17, 1, 12) C := submatrix(CC, 9, 17, 1, 12) D := submatrix(DD, 9, 17, 1, 12)

D = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	140.5	200.6	300.1	397.9	458.8	476.5	461.8	423.5	363	282.9	199.7	142.6
2	208.9	274	373.5	466.7	523.3	540.5	528.6	492.7	430.7	345.8	259.7	204.5
3	253	322.4	420.8	509.2	562.2	580	570.9	536.3	471.4	381.4	293.4	241.5
4	269.7	342.5	438.8	522.3	573	592.2	585.9	551.4	482.3	387.3	298.5	251
5	258	332.8	426.2	505.4	554.8	576.3	572.4	536.8	462.7	363.1	274.7	232.5
6	218.6	294.2	384	459.4	508.9	533.4	531.4	493.6	414	310.3	223.5	187.1
7	154.1	229.1	314.9	387.6	438.5	466.4	465.7	424.8	339.4	232.7	148.5	118
8	69.1	142.1	223.8	294.7	348.3	379.9	379.8	334.9	244	135.4	54.8	29.8
9	8.9	39.1	116.8	187.3	244.5	279.8	279.5	230.2	134.4	25.2	8.9	8.9

$t := 1, 2 .. 9$

... new iteration indices for the matrix calculations

$i := 1, 2 .. 12$

Lux needed from artificial lighting for any hour in the year:

$AL_{t,i} := \mathrm{if}\left(A_{t,i} > 500 \cdot lx, 0 \cdot lx, 500 \cdot lx - A_{t,i}\right)$

AL = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	192.3	60.5	0	0	0	0	0	0	0	0	62.5	187.7
2	42.4	0	0	0	0	0	0	0	0	0	0	52.1
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	21.3	0	0	0	0	0	0	0	0	0	10.4	90.2
7	162.4	0	0	0	0	0	0	0	0	0	174.7	241.6
8	348.7	188.7	9.8	0	0	0	0	0	0	203.3	379.9	434.6
9	480.5	414.4	244.3	89.8	0	0	0	0	205.6	444.8	480.5	480.5

$BL_{t,i} := \mathrm{if}\left(B_{t,i} > 500 \cdot lx, 0 \cdot lx, 500 \cdot lx - B_{t,i}\right)$

BL = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	292.4	203.5	56.6	0	0	0	0	0	0	82	204.9	289.3
2	191.3	95.1	0	0	0	0	0	0	0	0	116.2	197.8
3	126.2	23.6	0	0	0	0	0	0	0	0	66.4	143.2
4	101.4	0	0	0	0	0	0	0	0	0	58.9	129.1
5	118.8	8.2	0	0	0	0	0	0	0	0	94.1	156.5
6	177.1	65.3	0	0	0	0	0	0	0	41.4	169.7	223.5
7	272.3	161.4	34.6	0	0	0	0	0	0	156.2	280.5	325.7
8	397.9	290	169.3	64.5	0	0	0	5.1	139.4	299.9	419	455.9
9	486.8	442.3	327.5	223.3	138.8	86.5	87	159.8	301.4	462.7	486.8	486.8

$CL_{t,i} := if(C_{t,i} > 500 \cdot lx, 0 \cdot lx, 500 \cdot lx - C_{t,i})$

CL = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	337.9	268.5	153.8	41	0	0	0	11.5	81.2	173.7	269.6	335.5
2	259	183.8	69.1	0	0	0	0	0	3.1	101	200.3	264.1
3	208.1	128	14.5	0	0	0	0	0	0	59.9	161.5	221.4
4	188.8	104.9	0	0	0	0	0	0	0	53.1	155.6	210.4
5	202.4	116	8.3	0	0	0	0	0	0	81.1	183.1	231.8
6	247.9	160.6	57	0	0	0	0	0	22.4	142	242.1	284.1
7	322.2	235.6	136.7	52.9	0	0	0	9.9	108.4	231.5	328.6	363.9
8	420.3	336	241.8	159.9	98.2	61.7	61.9	113.6	218.4	343.7	436.8	465.6
9	489.7	454.9	365.3	283.9	218	177.2	177.5	234.4	344.9	470.9	489.7	489.7

$DL_{t,i} := if(D_{t,i} > 500 \cdot lx, 0 \cdot lx, 500 \cdot lx - D_{t,i})$

DL = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	359.5	299.4	199.9	102.1	41.2	23.5	38.2	76.5	137	217.1	300.3	357.4
2	291.1	226	126.5	33.3	0	0	0	7.3	69.3	154.2	240.3	295.5
3	247	177.6	79.2	0	0	0	0	0	28.6	118.6	206.6	258.5
4	230.3	157.5	61.2	0	0	0	0	0	17.7	112.7	201.5	249
5	242	167.2	73.8	0	0	0	0	0	37.3	136.9	225.3	267.5
6	281.4	205.8	116	40.6	0	0	0	6.4	86	189.7	276.5	312.9
7	345.9	270.9	185.1	112.4	61.5	33.6	34.3	75.2	160.6	267.3	351.5	382
8	430.9	357.9	276.2	205.3	151.7	120.1	120.2	165.1	256	364.6	445.2	470.2
9	491.1	460.9	383.2	312.7	255.5	220.2	220.5	269.8	365.6	474.8	491.1	491.1

LUMINAIRES SELECTION

The next step is to place luminaires on the ceiling and then calculate the possible energy savings. The number of luminaires is determined using the coefficient of utilization method, to achieve 500 lx average horizontal illuminance on the working plane.

Room cavity ratio: $RCR := \frac{5 \cdot HT \cdot (LT + WT)}{LT \cdot WT}$ $RCR = 6$

Floor cavity ratio: $FCR := \frac{5 \cdot WUP \cdot (LT + WT)}{LT \cdot WT}$ $FCR = 1.6$

Effective floor reflectance (from tables): 29%

We assume that there is no ceiling cavity (the luminaires are mounted on the ceiling).The luminaire selected is the Paramount Industries Inc., F2448H4-E0. It has four fluorescent lamps and 3850 lm/lamp. The light distriution is direct with quadrilateral symmetry. It is assumed that the lamps are 60W. From the coefficients of utilization table provided, the CU is 0.48 (for ceiling reflectance 80%, walls reflectance 70% and effective floor reflectance 20%. Since the efective floor reflectance is different from 20%, we have to multiply by a correction factor, which is found 1.052 from tables, so

$CU := 0.48 \cdot 1.052$ $CU = 0.505$

Average illuminance on working plane (target): $E_{wp} := 500 \cdot lx$

Work plane area (assume all office area): $A_{wp} := LT \cdot WT$

Light loss factor: $LLF := 0.8$

Total lumens required: $\Phi := \dfrac{E_{wp} \cdot A_{wp}}{CU \cdot LLF}$ $\quad \Phi = 3.094 \times 10^4 \, lm$

Number of tubes reuired: $NT := \dfrac{\Phi}{3850 \cdot lm}$ $\quad NT = 8.037$

Number of luminaires required: $N := \dfrac{NT}{4}$ $\quad N = 2.009$

That means that we need only 2 luminaires to keep the average illuminance on the working plane near 500 lx. The 2 luminaires were placed in the office space using the Lumen-Micro software. Their coordinates are:

$L1(1.88, 2.5, 3)$ ... above point B

$L2(3.76, 2.5, 3)$ ... above point D

Knowing the candela distribution of the luminaires, we can determine the illuminance on points A,B,C,D due to each luminaire. Doing the calculations, we find:

$E_{AL1} := 388.4 \cdot lx$ $\quad E_{AL2} := 97.6 \cdot lx$ $\quad E_{AL1L2} := E_{AL1} + E_{AL2}$ $\quad E_{AL1L2} = 486 \, lx$

$E_{BL1} := 523 \cdot lx$ $\quad E_{BL2} := 198 \cdot lx$ $\quad E_{BL1L2} := E_{BL1} + E_{BL2}$ $\quad E_{BL1L2} = 721 \, lx$

$E_{CL1} := 388.4 \cdot lx$ $\quad E_{CL2} := 388.4 \cdot lx$ $\quad E_{CL1L2} := E_{CL1} + E_{CL2}$ $\quad E_{CL1L2} = 776.8 \, lx$

$E_{DL1} := 198 \cdot lx$ $\quad E_{DL2} := 523 \cdot lx$ $\quad E_{DL1L2} := E_{DL1} + E_{DL2}$ $\quad E_{DL1L2} = 721 \, lx$

These are the illuminances on points A,B,C and D when the lamps are give their 100% output. We want to dim the lamps so that on each of the points A, B, C, D we have at least 500 lx. We assume that there are 4 dimming levels for the lamps: 25%, 50%, 75% and 100%. Since the lowest values of illuminance happen on point D, we will start from diming luminaire L2, above point D. Assume that the ratio of the output of the lamps of luminaire 2 (dimming level) is : $dim2_{t,i}$

$$DIM2_{t,i} := \text{if}\left(0 < \frac{DL_{t,i}}{E_{DL2}} \le 0.25, 0.25, \text{if}\left(0.25 < \frac{DL_{t,i}}{E_{DL2}} \le 0.5, 0.5, \text{if}\left(0.5 < \frac{DL_{t,i}}{E_{DL2}} \le 0.75, 0.75, \text{if}\left(\frac{DL_{t,i}}{E_{DL2}} > 0.75, 1, 0\right)\right)\right)\right)$$

DIM2 =

	1	2	3	4	5	6	7	8	9	10	11	12
1	0.75	0.75	0.5	0.25	0.25	0.25	0.25	0.25	0.5	0.5	0.75	0.75
2	0.75	0.5	0.25	0.25	0	0	0	0.25	0.25	0.5	0.5	0.75
3	0.5	0.5	0.25	0	0	0	0	0	0.25	0.25	0.5	0.5
4	0.5	0.5	0.25	0	0	0	0	0	0.25	0.25	0.5	0.5
5	0.5	0.5	0.25	0	0	0	0	0	0.25	0.5	0.5	0.75
6	0.75	0.5	0.25	0.25	0	0	0	0.25	0.25	0.5	0.75	0.75
7	0.75	0.75	0.5	0.25	0.25	0.25	0.25	0.25	0.5	0.75	0.75	0.75
8	1	0.75	0.75	0.5	0.5	0.25	0.25	0.5	0.5	0.75	1	1
9	1	1	0.75	0.75	0.5	0.5	0.5	0.75	0.75	1	1	1

After we have dimmed these lamps, the illuminance at points A, B, C and D will then be:

$DF_{t,i} := D_{t,i} + E_{DL2} \cdot DIM2_{t,i}$

DF = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	532.7	592.9	561.6	528.6	589.6	607.3	592.6	554.2	624.5	544.4	592	534.8
2	601.2	535.5	504.2	597.4	523.3	540.5	528.6	623.5	561.5	607.3	521.2	596.8
3	514.5	583.9	551.5	509.2	562.2	580	570.9	536.3	602.1	512.2	554.9	503
4	531.2	604	569.5	522.3	573	592.2	585.9	551.4	613.1	518.1	560	512.5
5	519.5	594.3	557	505.4	554.8	576.3	572.4	536.8	593.5	624.6	536.2	624.7
6	610.8	555.7	514.7	590.2	508.9	533.4	531.4	624.4	544.7	571.8	615.8	579.4
7	546.4	621.4	576.4	518.3	569.2	597.2	596.4	555.5	600.9	624.9	540.8	510.2
8	592.1	534.4	616	556.2	609.8	510.7	510.5	596.4	505.5	527.7	577.8	552.8
9	531.9	562.1	509	579.5	506	541.3	541	622.5	526.7	548.2	531.9	531.9

$CF_{t,i} := C_{t,i} + E_{CL2} \cdot DIM2_{t,i}$

CF = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	453.4	522.8	540.4	556.1	626.4	646.9	629.9	585.6	613	520.5	521.7	455.8
2	532.3	510.4	528	635.5	603.7	623.6	609.9	665.5	594	593.2	493.9	527.2
3	486.1	566.2	582.6	587.4	648.7	669.1	658.7	618.8	640.9	537.2	532.7	472.8
4	505.4	589.3	603.3	602.6	661.1	683.2	675.9	636.1	653.5	544	538.6	483.8
5	491.8	578.2	588.8	583.1	640.1	664.9	660.3	619.3	630.9	613.1	511.1	559.5
6	543.4	533.6	540.1	627.1	587.1	615.4	613.1	666.6	574.7	552.2	549.2	507.2
7	469.1	555.7	557.5	544.2	603	635.2	634.4	587.2	585.8	559.8	462.7	427.4
8	468.1	455.3	549.5	534.3	596	535.4	535.2	580.6	475.8	447.6	451.6	422.8
9	398.7	433.5	426	507.4	476.2	517	516.7	556.9	446.4	417.5	398.7	398.7

$BF_{t,i} := B_{t,i} + E_{BL2} \cdot DIM2_{t,i}$

BF = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	356.1	445	542.4	637.4	727.5	753.6	731.9	675.2	635.4	517	443.6	359.2
2	457.2	503.9	601.4	739.1	773.2	798.7	781.1	777.5	685.9	610	482.8	450.7
3	472.8	575.4	671.3	752.3	830.8	857	843.6	792.5	746	613.1	532.6	455.8
4	497.6	605	697.8	771.8	846.7	875	865.7	814.7	762.2	621.8	540.1	469.9
5	480.2	590.8	679.3	746.8	819.8	851.5	845.8	793.2	733.2	635.5	504.9	492
6	471.4	533.7	616.9	728.3	752	788.2	785.2	778.9	661.2	557.6	478.8	425
7	376.2	487.1	564.4	622.2	697.4	738.7	737.6	677.2	600.5	492.3	368	322.8
8	300.1	358.5	479.2	534.5	613.6	610.9	610.7	593.9	459.6	348.6	279	242.1
9	211.2	255.7	321	425.2	460.2	512.5	512	488.7	347.1	235.3	211.2	211.2

$AF_{t,i} := A_{t,i} + E_{AL2} \cdot DIM2_{t,i}$

AF = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	380.9	512.7	706.1	895.9	$1 \cdot 10^3$	$1.1 \cdot 10^3$	$1 \cdot 10^3$	951.9	844	668.4	510.7	385.5
2	530.8	649	842.5	$1 \cdot 10^3$	$1.1 \cdot 10^3$	$1.2 \cdot 10^3$	$1.2 \cdot 10^3$	$1.1 \cdot 10^3$	967.8	806.3	617.7	521.1
3	602.9	755	946.1	$1.1 \cdot 10^3$	$1.2 \cdot 10^3$	$1.3 \cdot 10^3$	$1.3 \cdot 10^3$	$1.2 \cdot 10^3$	$1.1 \cdot 10^3$	859.9	691.5	577.8
4	639.6	798.9	985.5	$1.1 \cdot 10^3$	$1.3 \cdot 10^3$	$1.3 \cdot 10^3$	$1.3 \cdot 10^3$	$1.2 \cdot 10^3$	$1.1 \cdot 10^3$	872.8	702.7	598.7
5	613.9	777.8	958	$1.1 \cdot 10^3$	$1.2 \cdot 10^3$	$1.3 \cdot 10^3$	$1.3 \cdot 10^3$	$1.2 \cdot 10^3$	$1 \cdot 10^3$	844.1	650.5	582.4
6	551.9	693.2	865.4	$1 \cdot 10^3$	$1.1 \cdot 10^3$	$1.2 \cdot 10^3$	$1.2 \cdot 10^3$	$1.1 \cdot 10^3$	931.1	728.5	562.8	483
7	410.8	575.1	738.6	873.3	984.8	$1 \cdot 10^3$	$1 \cdot 10^3$	954.8	792.2	582.9	398.5	331.6
8	248.9	384.5	563.4	694.4	811.7	856.6	856.2	782.4	583.3	369.9	217.7	163
9	117.1	183.2	328.9	483.4	584.3	661.7	661	577.5	367.6	152.8	117.1	117.1

Now the illuminance on D at all times of the year is greater than 500 lx. However, on points A, B and C there are still some values below 500 lx. Looking at point B now, (the other luminaire is above point B and between points A and C), we have:

$$DIM1_{t,i} := \text{if}\left(0 < \frac{500 \cdot lx - BF_{t,i}}{E_{BL1}} \le 0.25, 0.25, \text{if}\left(0.25 < \frac{500 \cdot lx - BF_{t,i}}{E_{BL1}} \le 0.5, 0.5, \text{if}\left(0.5 < \frac{500 \cdot lx - BF_{t,i}}{E_{BL1}} \le 0.75, 0.75, \text{if}\left(0.75 < \frac{500 \cdot lx -}{E_{BL}}\right.\right.\right.\right.$$

DIM1 =

	1	2	3	4	5	6	7	8	9	10	11	12
1	0.5	0.25	0	0	0	0	0	0	0	0	0.25	0.5
2	0.25	0	0	0	0	0	0	0	0	0	0.25	0.25
3	0.25	0	0	0	0	0	0	0	0	0	0	0.25
4	0.25	0	0	0	0	0	0	0	0	0	0	0.25
5	0.25	0	0	0	0	0	0	0	0	0	0	0.25
6	0.25	0	0	0	0	0	0	0	0	0	0.25	0.25
7	0.25	0.25	0	0	0	0	0	0	0	0.25	0.5	0.5
8	0.5	0.5	0.25	0	0	0	0	0	0.25	0.5	0.5	0.5
9	0.75	0.5	0.5	0.25	0.25	0	0	0.25	0.5	0.75	0.75	0.75

Then the final illuminance on points A, B, C and D at all times of the year will be:

$$IllumB_{t,i} := BF_{t,i} + DIM1_{t,i} \cdot E_{BL1}$$

IllumB = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	617.6	575.7	542.4	637.4	727.5	753.6	731.9	675.2	635.4	517	574.4	620.7
2	587.9	503.9	601.4	739.1	773.2	798.7	781.1	777.5	685.9	610	613.6	581.4
3	603.6	575.4	671.3	752.3	830.8	857	843.6	792.5	746	613.1	532.6	586.6
4	628.3	605	697.8	771.8	846.7	875	865.7	814.7	762.2	621.8	540.1	600.7
5	611	590.8	679.3	746.8	819.8	851.5	845.8	793.2	733.2	635.5	504.9	622.8
6	602.2	533.7	616.9	728.3	752	788.2	785.2	778.9	661.2	557.6	609.5	555.7
7	507	617.8	564.4	622.2	697.4	738.7	737.6	677.2	600.5	623.1	629.5	584.3
8	561.6	620	609.9	534.5	613.6	610.9	610.7	593.9	590.4	610.1	540.5	503.6
9	603.4	517.2	582.5	556	591	512.5	512	619.4	608.6	627.5	603.4	603.4

$$IllumD_{t,i} := DF_{t,i} + DIM1_{t,i} \cdot E_{DL1}$$

IllumD = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	631.7	642.4	561.6	528.6	589.6	607.3	592.6	554.2	624.5	544.4	641.5	633.8
2	650.7	535.5	504.2	597.4	523.3	540.5	528.6	623.5	561.5	607.3	570.7	646.3
3	564	583.9	551.5	509.2	562.2	580	570.9	536.3	602.1	512.2	554.9	552.5
4	580.7	604	569.5	522.3	573	592.2	585.9	551.4	613.1	518.1	560	562
5	569	594.3	557	505.4	554.8	576.3	572.4	536.8	593.5	624.6	536.2	674.2
6	660.3	555.7	514.7	590.2	508.9	533.4	531.4	624.4	544.7	571.8	665.3	628.9
7	595.9	670.9	576.4	518.3	569.2	597.2	596.4	555.5	600.9	674.4	639.8	609.2
8	691.1	633.4	665.5	556.2	609.8	510.7	510.5	596.4	555	626.7	676.8	651.8
9	680.4	661.1	608	629	555.5	541.3	541	672	625.7	696.7	680.4	680.4

$$IllumC_{t,i} := CF_{t,i} + DIM1_{t,i} \cdot E_{CL1}$$

IllumC = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	647.6	619.9	540.4	556.1	626.4	646.9	629.9	585.6	613	520.5	618.8	650
2	629.4	510.4	528	635.5	603.7	623.6	609.9	665.5	594	593.2	591	624.3
3	583.2	566.2	582.6	587.4	648.7	669.1	658.7	618.8	640.9	537.2	532.7	569.9
4	602.5	589.3	603.3	602.6	661.1	683.2	675.9	636.1	653.5	544	538.6	580.9
5	588.9	578.2	588.8	583.1	640.1	664.9	660.3	619.3	630.9	613.1	511.1	656.6
6	640.5	533.6	540.1	627.1	587.1	615.4	613.1	666.6	574.7	552.2	646.3	604.3
7	566.2	652.8	557.5	544.2	603	635.2	634.4	587.2	585.8	656.9	656.9	621.6
8	662.3	649.5	646.6	534.3	596	535.4	535.2	580.6	572.9	641.8	645.8	617
9	690	627.7	620.2	604.5	573.3	517	516.7	654	640.6	708.8	690	690

$IllumA_{t,i} := AF_{t,i} + DIM1_{t,i} \cdot E_{AL1}$

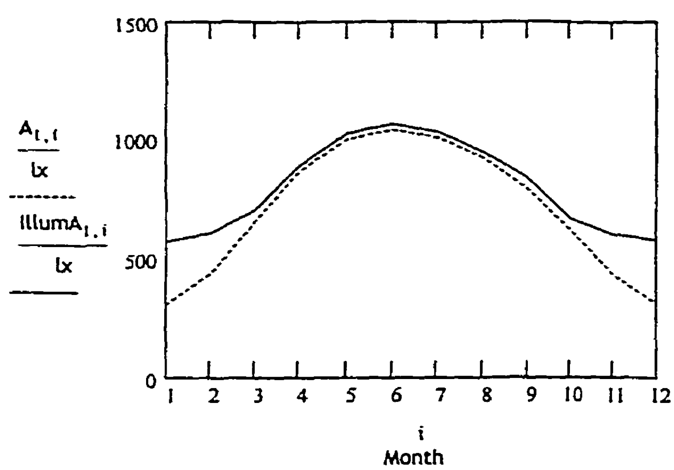
IllumA =

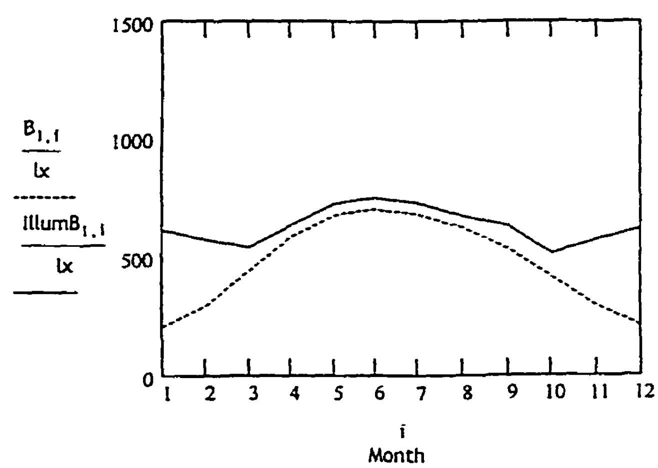
	1	2	3	4	5	6	7	8	9	10	11	12
1	575.1	609.8	706.1	895.9	$1\cdot10^3$	$1.1\cdot10^3$	$1\cdot10^3$	951.9	844	668.4	607.8	579.7
2	627.9	649	842.5	$1\cdot10^3$	$1.1\cdot10^3$	$1.2\cdot10^3$	$1.2\cdot10^3$	$1.1\cdot10^3$	967.8	806.3	714.8	618.2
3	700	755	946.1	$1.1\cdot10^3$	$1.2\cdot10^3$	$1.3\cdot10^3$	$1.3\cdot10^3$	$1.2\cdot10^3$	$1.1\cdot10^3$	859.9	691.5	674.9
4	736.7	798.9	985.5	$1.1\cdot10^3$	$1.3\cdot10^3$	$1.3\cdot10^3$	$1.3\cdot10^3$	$1.2\cdot10^3$	$1.1\cdot10^3$	872.8	702.7	695.8
5	711	777.8	958	$1.1\cdot10^3$	$1.2\cdot10^3$	$1.3\cdot10^3$	$1.3\cdot10^3$	$1.2\cdot10^3$	$1\cdot10^3$	844.1	650.5	679.5
6	649	693.2	865.4	$1\cdot10^3$	$1.1\cdot10^3$	$1.2\cdot10^3$	$1.2\cdot10^3$	$1.1\cdot10^3$	931.1	728.5	659.9	580.1
7	507.9	672.2	738.6	873.3	984.8	$1\cdot10^3$	$1\cdot10^3$	954.8	792.2	680	592.7	525.8
8	443.1	578.7	660.5	694.4	811.7	856.6	856.2	782.4	680.4	564.1	411.9	357.2
9	408.4	377.4	523.1	580.5	681.4	661.7	661	674.6	561.8	444.1	408.4	408.4

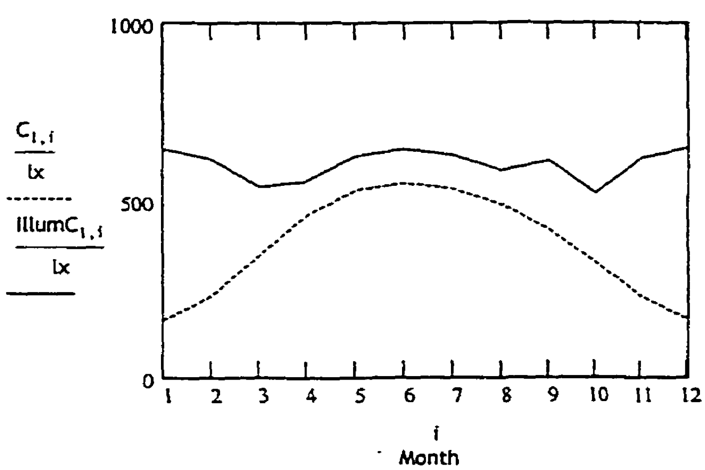
lx

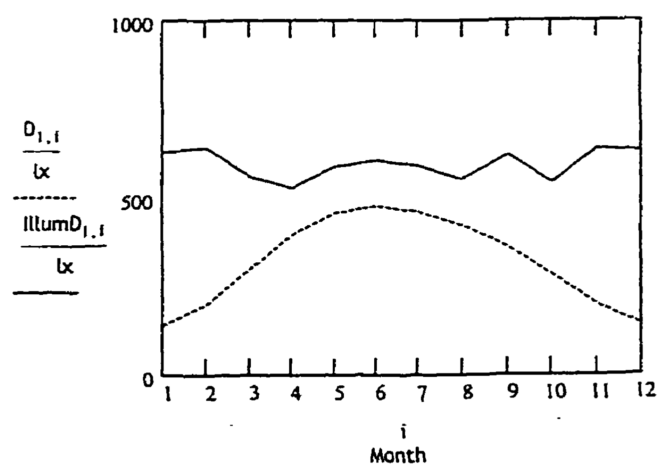
Now in all cases the illuminance is above 500lx at all times of the year, except for 2 hours in some winter afternoons at point A.

A graphical visualization is presented in the following figures. The illuminance on points A, B, C and D is shown for 9am of the identical day of each month only with natural daylight (dashed line) and with dimming of the lights (solid line). The results are very good and the illuminance levels are generally slightly above 500 lx, except for point A, where it can reach 1000 lx in summer mornings.









ESTIMATION OF ENERGY SAVINGS

Each lamp needs 60 input Watts and a ballast with 15 W is needed for each pair of lamps. Thus for each luminaire (4 lamps) the input Watts are 4x60 + 2x15 = 270 W. For an office with no daylighting control or on/off operation, the annual energy consumed due to electric lighting is:

luminaire input Watts* number of luminaires* hours per day* 360 days

$En_o := 270 \cdot W \cdot 2 \cdot 8hr \cdot 360 \qquad En_o = 5.599 \times 10^9 J$

With the Vision Control window and the dimming of the lights, the energy consumed in a year will be:

$$En := 30 \cdot \sum_{t=1}^{8} \sum_{i=1}^{12} \left(DIM1_{t,i} - DIM2_{t,i} \right) \cdot 270 \cdot W \cdot hr \qquad En = 1.334 \times 10^9 J$$

Thus the energy savings will be: $En_o - En = 4.265 \times 10^9 J$ or $\frac{En_o - En}{En_o} = 0.762$ or 76.2%

APPENDIX E:

CALCULATION OF THE OPTIMUM BLIND TILT ANGLE ON CLEAR DAYS FOR AVOIDING GLARE

From Fig. 4.4, it is:

$$tan(\alpha) = \frac{r - r \cdot sin(\beta - 90°)}{r \cdot cos(\beta - 90°)} = \frac{1 - sin(\beta - 90°)}{cos(\beta - 90°)}$$

In order to calculate the optimum blind tilt angle, β, for all the working hours on a clear day (as a function of solar time, t and day number, n), the above equation must be solved for β. Then β will be a function of solar altitude (a), which is a function of n and t. In the above equation, tan(a) is named a and β-$90°$ is named x. Thus, the equation becomes:

$a = \frac{1 - sin(x)}{cos(x)}$ Next, by setting $b=90°-x$, the equation becomes: $a = \frac{1 - cos(b)}{sin(b)}$

Replacing b by $\frac{2 \cdot b}{2}$, it is: $a = \frac{1 - cos(\frac{2 \cdot b}{2})}{sin(\frac{2 \cdot b}{2})}$

Using the trigonometric equations:

$cos(2 \cdot x) = cos^2(x) - sin^2(x)$ and $sin(2 \cdot x) = 2 \cdot sin(x) \cdot cos(x)$, it is transformed into:

$a = \frac{1 - [cos^2(\frac{b}{2}) - sin^2(\frac{b}{2})]}{2 \cdot sin(\frac{b}{2}) \cdot cos(\frac{b}{2})}$ and because $1 - cos^2(\frac{b}{2}) = sin^2(\frac{b}{2})$, it becomes:

$a = \frac{2 \cdot sin^2(\frac{b}{2})}{2 \cdot sin(\frac{b}{2}) \cdot cos(\frac{b}{2})} \Rightarrow a = tan(\frac{b}{2})$. Solving for b, it is: $b = 2 \cdot tan^{-1}(a)$.

Substituting,

$x = 90° - 2 \cdot tan^{-1}(a) \Rightarrow \beta - 90° = 90° - 2 \cdot tan^{-1}(a) \Rightarrow \beta = 180° - 2 \cdot tan^{-1}(a)$ and

replacing a with tan(a), finally β is found as a function of the solar altitude, a:

$\boldsymbol{\beta(n,t) = 180° - 2 \cdot \alpha(n,t)}$ or, as a function of solar time and day number.

APPENDIX F:

ILLUMINANCE LEVEL AND LIGHT DIMMING FACTORS CALCULATIONS FOR CLEAR DAYS (Mathcad 2000 program)

This quicksheet calculates the illuminance on each of the selected points for every hour in the year on clear days.

DAYLIGHT INCIDENT ON WINDOW

The horizontal illuminance under a clear sky from the sky can be calculated from the formula:

$$E_{hsky}(n,t) := \mathrm{if}\left[\alpha(n,t) > 0\cdot deg,\ 1000\cdot\left(0.8 + 15.5\cdot\sqrt{\sin(\alpha(n,t))}\right)\cdot lx,\ 0\cdot lx\right]$$

There is also the beam radiation (from the sun). This is calculated as follows:

$E_o := 127500\cdot lx$ ... average illuminance on a surface perpendicular to the sun's rays just outside earth's atmosphere

This should be adjusted for a given date to account for the elliptical shape of the earth's orbit around the sun. the correction factor for the day dn of the year is:

$$cr(n) := 1 + 0.033\cdot\cos\left(\frac{360\cdot n}{365}\right)$$

To obtain the solar illuminance Ep at sea level on the same day on a similarly oriented surface requires that we account for attenuation through the earth's atmosphere. Atmospheric attenuation is a function of the composition of the atmosphere and of the length of the path traversed by the sun's rays. It is expressed as:

$$E_p = E_o\cdot e^{-cc\cdot mo}$$

where cc is the optical atmospheric extinction coefficient and mo is the relative optical air mass. The quantity cc is found 0.21 for the clear sky from recent measurements. The relative optical air mass is of course a function of solar altitude:

$$mo(n,t) := \frac{1}{\sin\left(\alpha(n,t) + 10^{-10}\cdot deg\right)} \qquad cc := 0.21$$

Now we have the solar illuminance at sea level on a surface perpendicular to the sun's rays:

$$E_p(n,t) := E_o\cdot cr(n)\cdot e^{-cc\cdot mo(n,t)}$$

The solar illuminance on a horizontal surface will be:

$$E_{hsun}(n,t) := E_p(n,t) \cdot \sin(\alpha(n,t))$$

The solar illuminance (beam radiation) on the window (vertical surface) will be:

$$E_b(n,t) := E_p(n,t) \cdot \cos(\theta(n,t))$$

The total horizontal illuminance under a clear sky will be equal to:

$$E_h(n,t) := E_{hsun}(n,t) + E_{hsky}(n,t)$$

The illuminance incident on the window from the sky (since there is only diffuse light), will be equal to the diffuse horizontal illuminance multiplied by the view factor between the window and the sky, which is assumed 0.5 (window sees half of the sky):

$$E_{wsky}(n,t) := E_{hsky}(n,t) \cdot 0.5$$

There is also incident daylight on the window coming from the ground. This is equal to the total horizontal illuminance (on the ground) multiplied by the ground reflectance and the view factor between the window and the ground (which is also assumed 0.5) :

$\rho_{gr} := 0.2$. ground reflectance

$$E_{wgr}(n,t) := E_h(n,t) \cdot \rho_{gr} \cdot 0.5$$

The **total illuminance incident on the window** is equal to the sum of these three compartments:

$$E_w(n,t) := E_b(n,t) + E_{wgr}(n,t) + E_{wsky}(n,t)$$

DAYLIGHT TRANSMITTED THROUGH THE WINDOW

The daylight transmittance for clear day is a function of the blinds tilt angle,β and of the angle of incidence,θ :

$\beta(n,t) := \mathrm{if}(\alpha(n,t) > 45 \cdot \mathrm{deg}, 90 \cdot \mathrm{deg}, 180 \cdot \mathrm{deg} - 2 \cdot \alpha(n,t))$ ...optimum blind tilt angle to avoid glare, allow maximum daylight and maximize view

$\theta\tau(n,t) := \dfrac{\theta(n,t)}{\mathrm{deg}}$ $\beta\tau(n,t) := \dfrac{\beta(n,t)}{\mathrm{deg}}$ ... units transformations for calculations

$$\tau(n,t) := 0.55\cdot\exp\left[\frac{-(\beta\tau(n,t)-80)^2}{1900}\right]\cdot\left(-4.917\cdot10^{-7}\cdot\theta\tau(n,t)^4 + 0.00009\cdot\theta\tau(n,t)^3 - 0.005567\cdot\theta\tau(n,t)^2 + 0.13\cdot\theta\tau(n,t) + 0.004378\right)$$

Illuminance transmitted through window: $E_t(n,t) := E_w(n,t)\cdot\tau(n,t)$

LUMINOUS EXITANCE OF ALL INTERIOR SURFACES

Now the office space is considered as an enclosure with only one luminous source (the window) which emits diffuse light uniformily towards all directions (surfaces). The final luminous exitance of each surface will now be calculated after multiple reflections on every room interior surfaces. First, we represent the initial luminous exitances of the room interior surfaces in matrix form:

Matrix of initial luminous exitances:

$$M_o(n,t) := \begin{pmatrix} E_t(n,t) \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

View factors matrix:

$$F = \begin{pmatrix} 0 & 0 & 0.24 & 0.309 & 0.145 & 0.153 & 0.153 \\ 0 & 0 & 0.269 & 0.2 & 0.111 & 0.21 & 0.21 \\ 0.077 & 0.086 & 0 & 0.354 & 0.161 & 0.161 & 0.161 \\ 0.099 & 0.064 & 0.354 & 0 & 0.161 & 0.161 & 0.161 \\ 0.077 & 0.059 & 0.269 & 0.269 & 0 & 0.163 & 0.163 \\ 0.082 & 0.081 & 0.269 & 0.269 & 0.163 & 0 & 0.136 \\ 0.082 & 0.081 & 0.269 & 0.269 & 0.163 & 0.136 & 0 \end{pmatrix}$$

Surfaces reflectance matrix:

$$\rho := \begin{pmatrix} 0.1 \\ 0.7 \\ 0.3 \\ 0.8 \\ 0.7 \\ 0.7 \\ 0.7 \end{pmatrix} \quad \begin{pmatrix} \text{Window} \\ \text{"Wall containing window"} \\ \text{Floor} \\ \text{Ceiling} \\ \text{"Back wall"} \\ \text{"Right wall"} \\ \text{"Left wall"} \end{pmatrix}$$

The final illuminance of each interior surface after multiple reflections, can be calculated from the formula:

$$M_i = M_{o_i} + \rho_i\cdot\sum_{i=1}^{n} M_j\cdot F_{i,j}$$

Solving for the initial illuminances, it is:

$$M_{o_i} = M_i - \rho_i\cdot\sum_{i=1}^{n} M_j\cdot F_{i,j}$$ or, analytically:

$$M_{o_1} = M_1 - (\rho_1 \cdot M_1 \cdot F_{1,1} + ... + \rho_1 \cdot M_7 \cdot F_{1,7})$$

$$M_{o_2} = M_2 - (\rho_2 \cdot M_1 \cdot F_{2,1} + ... + \rho_2 \cdot M_7 \cdot F_{2,7})$$

....

$$M_{o_7} = M_7 - (\rho_7 \cdot M_1 \cdot F_{7,1} + ... + \rho_7 \cdot M_7 \cdot F_{7,7})$$

This system can be written in matrix form:

$$M_o = (I - TT) \cdot M$$

where I is the 7x7 identity matrix and TT is a matrix each element of which is equal to:

$$TT_{i,j} = \rho_i \cdot F_{i,j}$$

Once matrix TT is calculated, the final luminous exitance of each surface will be:

$$M_i = (I - TT)^{-1} \cdot M_{o_i}$$

$TT_{i,j} := \rho_i \cdot F_{i,j}$

$$TT = \begin{pmatrix} 0 & 0 & 0.024 & 0.031 & 0.014 & 0.015 & 0.015 \\ 0 & 0 & 0.188 & 0.14 & 0.077 & 0.147 & 0.147 \\ 0.023 & 0.026 & 0 & 0.106 & 0.048 & 0.048 & 0.048 \\ 0.079 & 0.051 & 0.284 & 0 & 0.129 & 0.129 & 0.129 \\ 0.054 & 0.041 & 0.188 & 0.188 & 0 & 0.114 & 0.114 \\ 0.057 & 0.057 & 0.188 & 0.188 & 0.114 & 0 & 0.095 \\ 0.057 & 0.057 & 0.188 & 0.188 & 0.114 & 0.095 & 0 \end{pmatrix}$$

$I := \text{identity}(7)$

FINAL LUMINOUS EXITANCES OF ALL SURFACES: $M(n,t) := (I - TT)^{-1} \cdot M_o(n,t)$

$$M(15,9) = \begin{pmatrix} 1.008 \times 10^3 \\ 79.875 \\ 59.834 \\ 150.247 \\ 126.554 \\ 128.326 \\ 128.326 \end{pmatrix} \text{lx}$$

For clear day,
Day of year: 15 (Jan. 15),
Local Standard Time: 9 AM,
Blind tilt angle: 155.6 deg

$t := 9, 10 .. 17$

$$E_A(n,t) := \sum_{i=1}^{7} M(n,t)_i \cdot f_{A_i}$$ $E_A(15,9) = 367.56\ \text{lx}$

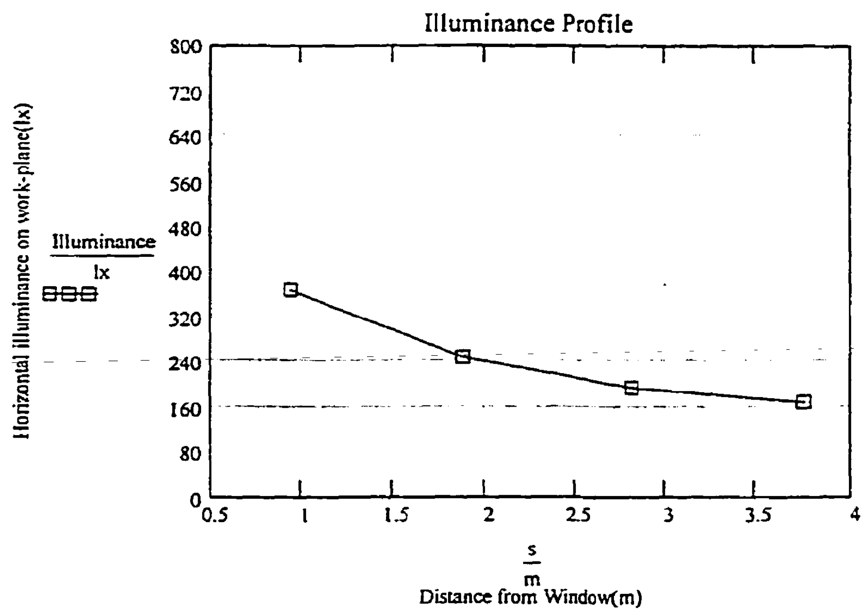
$$E_B(n,t) := \sum_{i=1}^{7} M(n,t)_i \cdot f_{B_i}$$ $E_B(15,9) = 247.963\ \text{lx}$

$$E_C(n,t) := \sum_{i=1}^{7} M(n,t)_i \cdot f_{C_i}$$ $E_C(15,9) = 193.603\ \text{lx}$

$$E_D(n,t) := \sum_{i=1}^{7} M(n,t)_i \cdot f_{D_i}$$ $E_D(15,9) = 167.81\ \text{lx}$

ILLUMINANCE PROFILE OF THE ROOM (9am, January 15th):

$Illuminance_i :=$	$s_i :=$
$E_A(15,9)$	0.94
$E_B(15,9)$	1.88
$E_C(15,9)$	2.82
$E_D(15,9)$	3.76



This section calculates the light dimming factors for every hour of the year and an estimation of possible energy savings for clear days.

$t := 9, 10..17$ ...Local Standard Time

$i := 1, 2..12$ ... month number

$n_i := 30 \cdot i - 15$ ...Day Number of Year

$E_A(n_i, t) =$

	1
1	367.56
2	$1.027 \cdot 10^3$
3	$3.426 \cdot 10^3$
4	$7.278 \cdot 10^3$
5	$8.535 \cdot 10^3$
6	$7.367 \cdot 10^3$

lx

This array contains all the illuminance values (for all days and times) on point A, in one column. It is more effective to have this array in 2D matrix form. The 12 columns represent the months (or days) and the rows the time of the day.

The same is done for points B, C and D :

$E_B(n_i, t) =$

	1
1	247.963
2	692.607
3	$2.311 \cdot 10^3$
4	$4.91 \cdot 10^3$
5	$5.758 \cdot 10^3$
6	$4.97 \cdot 10^3$

lx

$E_C(n_i, t) =$

	1
1	193.603
2	540.77
3	$1.804 \cdot 10^3$
4	$3.834 \cdot 10^3$
5	$4.496 \cdot 10^3$
6	$3.88 \cdot 10^3$

lx

$E_D(n_i, t) =$

	1
1	167.81
2	468.725
3	$1.564 \cdot 10^3$
4	$3.323 \cdot 10^3$
5	$3.897 \cdot 10^3$
6	$3.363 \cdot 10^3$

lx

$AA_{t,i} := E_A(n_i, t)$ $BB_{t,i} := E_B(n_i, t)$ $CC_{t,i} := E_C(n_i, t)$ $DD_{t,i} := E_D(n_i, t)$ ... 2D matrices

We are only interested in the hours between 9am and 5pm, so we can extract the submatrix containing only these hours:

$A := \text{submatrix}(AA, 9, 17, 1, 12)$ $B := \text{submatrix}(BB, 9, 17, 1, 12)$ $C := \text{submatrix}(CC, 9, 17, 1, 12)$ $D := \text{submatrix}(DD, 9, 17, 1, 12)$

$t := 1, 2..9$

$i := 1, 2..12$

... new iteration indices for the matrix calculations

Lux needed from artificial lighting for any time/day:

$AL_{t,i} := \text{if}\left(A_{t,i} > 500\cdot lx, 0\cdot lx, 500\cdot lx - A_{t,i}\right)$

AL =

	1	2	3	4	5	6	7	8	9	10	11	12
1	132.4	0	0	0	0	0	0	0	0	0	0	62
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	151.2	0	0	0	0	0	0	0	0	0	214.9	345.1
8	473.1	276.1	0	164.1	551.7	570.4	568.8	461.8	81.7	373.8	487.9	496.9
9	500	495.8	485.6	505.4	513.9	523.1	522.6	511.1	502	499.1	500	500

lx

$BL_{t,i} := \text{if}\left(B_{t,i} > 500\cdot lx, 0\cdot lx, 500\cdot lx - B_{t,i}\right)$

BL =

	1	2	3	4	5	6	7	8	9	10	11	12
1	252	0	0	0	0	0	0	0	0	0	0	204.5
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	264.7	0	0	0	0	0	0	0	0	0	307.7	395.5
8	481.9	349	68.4	273.4	534.9	547.5	546.4	474.2	217.8	414.9	491.8	497.9
9	500	497.2	490.3	503.6	509.4	515.6	515.2	507.5	501.3	499.4	500	500

lx

$CL_{t,i} := \text{if}\left(C_{t,i} > 500\cdot lx, 0\cdot lx, 500\cdot lx - C_{t,i}\right)$

CL =

	1	2	3	4	5	6	7	8	9	10	11	12
1	306.4	0	0	0	0	0	0	0	0	0	0	269.3
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	87.7
7	316.3	0	0	0	0	60.4	0	0	0	0	349.8	418.4
8	485.9	382.1	163	323.1	527.2	537.1	536.2	479.9	279.7	433.5	493.6	498.4
9	500	497.8	492.4	502.8	507.3	512.2	511.9	505.8	501	499.5	500	500

lx

$DL_{t,i} := \text{if}(D_{t,i} > 500\cdot lx, 0\cdot lx, 500\cdot lx - D_{t,i})$

DL = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	332.2	31.3	0	0	0	0	0	0	0	0	0	300
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	142.7
7	340.8	0	0	0	0	119	0	0	0	0	369.8	429.3
8	487.7	397.8	207.9	346.6	523.6	532.1	531.4	482.6	309	442.4	494.5	498.6
9	500	498.1	493.4	502.5	506.3	510.5	510.3	505.1	500.9	499.6	500	500

LUMINAIRES SELECTION

The next step is to place luminaires on the ceiling and then calculate the possible energy savings. The number of luminaires is determined using the coefficient of utilization method, to achieve 500 lx average horizontal illuminance on the working plane.

Room cavity ratio: $RCR := \frac{5\cdot HT\cdot(LT + WT)}{LT\cdot WT}$ $RCR = 6$

Floor cavity ratio: $FCR := \frac{5\cdot WUP\cdot(LT + WT)}{LT\cdot WT}$ $FCR = 1.6$

Effective floor reflectance (from tables): 29%

We assume that there is no ceiling cavity (the luminaires are mounted on the ceiling).The luminaire selected is the Paramount Industries Inc., F2448H4-E0. It has four fluorescent lamps and 3850 lm/lamp. The light distriution is direct with quadrilateral symmetry. It is assumed that the lamps are 60W. From the coefficients of utilization table provided, the CU is 0.48 (for ceiling reflectance 80%, walls reflectance 70% and effective floor reflectance 20%. Since the efective floor reflectance is different from 20%, we have to multiply by a correction factor, which is found 1.052 from tables, so

$CU := 0.48\cdot 1.052$ $CU = 0.505$

Average illuminance on working plane (target): $E_{wp} := 500\cdot lx$

Work plane area (assume all office area): $A_{wp} := LT\cdot WT$

Light loss factor: $LLF := 0.8$

Total lumens required: $\Phi := \frac{E_{wp}\cdot A_{wp}}{CU\cdot LLF}$ $\Phi = 3.094 \times 10^4\, lm$

Number of tubes reuired: $NT := \frac{\Phi}{3850 \cdot lm}$ $NT = 8.037$

Number of luminaires required: $N := \frac{NT}{4}$ $N = 2.009$

That means that we need only 2 luminaires to keep the average illuminance on the working plane near 500 lx. The 2 luminaires were placed in the office space using the Lumen-Micro software. Their coordinates are:

L1(1.88,2.5,3) ... above point B

L2(3.76,2.5,3) ... above point D

Knowing the candela distribution of the luminaires, we can determine the illuminance on points A,B,C,D due to each luminaire. Doing the calculations, we find:

$E_{AL1} := 388.4 \cdot lx$ $E_{AL2} := 97.6 \cdot lx$ $E_{AL1L2} := E_{AL1} + E_{AL2}$ $E_{AL1L2} = 486\ lx$

$E_{BL1} := 523 \cdot lx$ $E_{BL2} := 198 \cdot lx$ $E_{BL1L2} := E_{BL1} + E_{BL2}$ $E_{BL1L2} = 721\ lx$

$E_{CL1} := 388.4 \cdot lx$ $E_{CL2} := 388.4 \cdot lx$ $E_{CL1L2} := E_{CL1} + E_{CL2}$ $E_{CL1L2} = 776.8\ lx$

$E_{DL1} := 198 \cdot lx$ $E_{DL2} := 523 \cdot lx$ $E_{DL1L2} := E_{DL1} + E_{DL2}$ $E_{DL1L2} = 721\ lx$

These are the illuminances on points A,B,C and D when the lamps are give their 100% output. We want to dim the lamps so that on each of the points A, B, C, D we have at least 500 lx. We assume that there are 4 dimming levels for the lamps: 25%, 50%, 75% and 100%. Since the lowest values of illuminance happen on point D, we will start from diming luminaire L2, above point D. Assume that the ratio of the output of the lamps of luminaire 2 (dimming level) is :

$$DIM2_{t,i} := \text{if}\left(0 < \frac{DL_{t,i}}{E_{DL2}} \le 0.25, 0.25, \text{if}\left(0.25 < \frac{DL_{t,i}}{E_{DL2}} \le 0.5, 0.5, \text{if}\left(0.5 < \frac{DL_{t,i}}{E_{DL2}} \le 0.75, 0.75, \text{if}\left(\frac{DL_{t,i}}{E_{DL2}} > 0.75, 1, 0\right)\right)\right)\right)$$

DIM2 =

	1	2	3	4	5	6	7	8	9	10	11	12
1	0.75	0.25	0	0	0	0	0	0	0	0	0	0.75
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0.5
7	0.75	0	0	0	0	0.25	0	0	0	0	0.75	1
8	1	1	0.5	0.75	1	1	1	1	0.75	1	1	1
9	1	1	1	1	1	1	1	1	1	1	1	1

After we have dimmed these lamps, the illuminance at points A, B, C and D will then be:

$DF_{t,i} := D_{t,i} + E_{DL2} \cdot DIM2_{t,i}$

DF = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	560.1	599.5	$1.6\cdot10^{3}$	$3.3\cdot10^{3}$	$3.9\cdot10^{3}$	$3.4\cdot10^{3}$	$3.3\cdot10^{3}$	$3.6\cdot10^{3}$	$2.9\cdot10^{3}$	$1.5\cdot10^{3}$	530.8	592.2
2	737.2	$1.6\cdot10^{3}$	$3.5\cdot10^{3}$	$4.7\cdot10^{3}$	$4.6\cdot10^{3}$	$4.2\cdot10^{3}$	$4.1\cdot10^{3}$	$4.6\cdot10^{3}$	$4.8\cdot10^{3}$	$3.2\cdot10^{3}$	$1.5\cdot10^{3}$	755.4
3	$1.5\cdot10^{3}$	$3.1\cdot10^{3}$	$5.1\cdot10^{3}$	$4.9\cdot10^{3}$	$4.8\cdot10^{3}$	$4.5\cdot10^{3}$	$4.4\cdot10^{3}$	$4.9\cdot10^{3}$	$5.5\cdot10^{3}$	$4.5\cdot10^{3}$	$2.4\cdot10^{3}$	$1.4\cdot10^{3}$
4	$1.8\cdot10^{3}$	$3.7\cdot10^{3}$	$5.4\cdot10^{3}$	$4.9\cdot10^{3}$	$4.7\cdot10^{3}$	$4.3\cdot10^{3}$	$4.4\cdot10^{3}$	$4.9\cdot10^{3}$	$5.3\cdot10^{3}$	$4.3\cdot10^{3}$	$2.3\cdot10^{3}$	$1.5\cdot10^{3}$
5	$1.3\cdot10^{3}$	$2.9\cdot10^{3}$	$4.7\cdot10^{3}$	$4.6\cdot10^{3}$	$4.1\cdot10^{3}$	$3.7\cdot10^{3}$	$3.8\cdot10^{3}$	$4.5\cdot10^{3}$	$5\cdot10^{3}$	$3.1\cdot10^{3}$	$1.4\cdot10^{3}$	945
6	596.9	$1.6\cdot10^{3}$	$3.3\cdot10^{3}$	$3.9\cdot10^{3}$	$2.9\cdot10^{3}$	$2.3\cdot10^{3}$	$2.6\cdot10^{3}$	$3.6\cdot10^{3}$	$3.7\cdot10^{3}$	$1.7\cdot10^{3}$	566.3	618.8
7	551.5	585.7	$1.5\cdot10^{3}$	$1.8\cdot10^{3}$	934	511.8	781.3	$1.7\cdot10^{3}$	$1.6\cdot10^{3}$	524.8	522.4	593.7
8	535.3	625.2	553.6	545.6	499.4	490.9	491.6	540.4	583.2	580.6	528.5	524.4
9	523	524.9	529.6	520.5	516.7	512.5	512.7	517.9	522.1	523.4	523	523

$CF_{t,i} := C_{t,i} + E_{CL2} \cdot DIM2_{t,i}$

CF = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	484.9	637.9	$1.8\cdot10^{3}$	$3.8\cdot10^{3}$	$4.5\cdot10^{3}$	$3.9\cdot10^{3}$	$3.8\cdot10^{3}$	$4.2\cdot10^{3}$	$3.3\cdot10^{3}$	$1.7\cdot10^{3}$	612.3	522
2	850.5	$1.9\cdot10^{3}$	$4\cdot10^{3}$	$5.4\cdot10^{3}$	$5.3\cdot10^{3}$	$4.8\cdot10^{3}$	$4.7\cdot10^{3}$	$5.3\cdot10^{3}$	$5.6\cdot10^{3}$	$3.7\cdot10^{3}$	$1.7\cdot10^{3}$	871.5
3	$1.8\cdot10^{3}$	$3.6\cdot10^{3}$	$5.9\cdot10^{3}$	$5.7\cdot10^{3}$	$5.5\cdot10^{3}$	$5.2\cdot10^{3}$	$5.1\cdot10^{3}$	$5.6\cdot10^{3}$	$6.3\cdot10^{3}$	$5.2\cdot10^{3}$	$2.7\cdot10^{3}$	$1.6\cdot10^{3}$
4	$2.1\cdot10^{3}$	$4.2\cdot10^{3}$	$6.2\cdot10^{3}$	$5.7\cdot10^{3}$	$5.4\cdot10^{3}$	$5\cdot10^{3}$	$5\cdot10^{3}$	$5.6\cdot10^{3}$	$6.2\cdot10^{3}$	$5\cdot10^{3}$	$2.6\cdot10^{3}$	$1.7\cdot10^{3}$
5	$1.5\cdot10^{3}$	$3.3\cdot10^{3}$	$5.4\cdot10^{3}$	$5.3\cdot10^{3}$	$4.8\cdot10^{3}$	$4.2\cdot10^{3}$	$4.4\cdot10^{3}$	$5.2\cdot10^{3}$	$5.7\cdot10^{3}$	$3.6\cdot10^{3}$	$1.6\cdot10^{3}$	$1.1\cdot10^{3}$
6	688.6	$1.8\cdot10^{3}$	$3.8\cdot10^{3}$	$4.5\cdot10^{3}$	$3.3\cdot10^{3}$	$2.6\cdot10^{3}$	$3\cdot10^{3}$	$4.2\cdot10^{3}$	$4.3\cdot10^{3}$	$1.9\cdot10^{3}$	653.3	606.5
7	475	675.7	$1.7\cdot10^{3}$	$2.1\cdot10^{3}$	$1.1\cdot10^{3}$	536.7	901.4	$2\cdot10^{3}$	$1.8\cdot10^{3}$	605.4	441.5	470
8	402.5	506.3	531.2	468.2	361.2	351.3	352.2	408.5	511.6	454.9	394.8	390
9	388.4	390.6	396	385.6	381.1	376.2	376.5	382.6	387.4	388.9	388.4	388.4

$BF_{t,i} := B_{t,i} + E_{BL2} \cdot DIM2_{t,i}$

BF = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	396.5	742.1	$2.3\cdot10^{3}$	$4.9\cdot10^{3}$	$5.8\cdot10^{3}$	$5\cdot10^{3}$	$4.9\cdot10^{3}$	$5.4\cdot10^{3}$	$4.3\cdot10^{3}$	$2.2\cdot10^{3}$	784.3	444
2	$1.1\cdot10^{3}$	$2.4\cdot10^{3}$	$5.2\cdot10^{3}$	$6.9\cdot10^{3}$	$6.7\cdot10^{3}$	$6.2\cdot10^{3}$	$6.1\cdot10^{3}$	$6.8\cdot10^{3}$	$7.1\cdot10^{3}$	$4.8\cdot10^{3}$	$2.2\cdot10^{3}$	$1.1\cdot10^{3}$
3	$2.3\cdot10^{3}$	$4.6\cdot10^{3}$	$7.5\cdot10^{3}$	$7.3\cdot10^{3}$	$7.1\cdot10^{3}$	$6.6\cdot10^{3}$	$6.5\cdot10^{3}$	$7.2\cdot10^{3}$	$8.1\cdot10^{3}$	$6.6\cdot10^{3}$	$3.5\cdot10^{3}$	$2\cdot10^{3}$
4	$2.7\cdot10^{3}$	$5.4\cdot10^{3}$	$8\cdot10^{3}$	$7.2\cdot10^{3}$	$6.9\cdot10^{3}$	$6.4\cdot10^{3}$	$6.4\cdot10^{3}$	$7.2\cdot10^{3}$	$7.9\cdot10^{3}$	$6.4\cdot10^{3}$	$3.4\cdot10^{3}$	$2.2\cdot10^{3}$
5	$2\cdot10^{3}$	$4.3\cdot10^{3}$	$6.9\cdot10^{3}$	$6.8\cdot10^{3}$	$6.1\cdot10^{3}$	$5.4\cdot10^{3}$	$5.6\cdot10^{3}$	$6.7\cdot10^{3}$	$7.3\cdot10^{3}$	$4.6\cdot10^{3}$	$2.1\cdot10^{3}$	$1.4\cdot10^{3}$
6	882	$2.3\cdot10^{3}$	$4.8\cdot10^{3}$	$5.7\cdot10^{3}$	$4.3\cdot10^{3}$	$3.3\cdot10^{3}$	$3.8\cdot10^{3}$	$5.3\cdot10^{3}$	$5.5\cdot10^{3}$	$2.4\cdot10^{3}$	836.8	627
7	383.8	865.4	$2.2\cdot10^{3}$	$2.7\cdot10^{3}$	$1.4\cdot10^{3}$	612.6	$1.2\cdot10^{3}$	$2.6\cdot10^{3}$	$2.3\cdot10^{3}$	775.4	340.8	302.5
8	216.1	349	530.6	375.1	163.1	150.5	151.6	223.8	430.7	283.1	206.2	200.1
9	198	200.8	207.7	194.4	188.6	182.4	182.8	190.5	196.7	198.6	198	198

$AF_{t,i} := A_{t,i} + E_{AL2} \cdot DIM2_{t,i}$

AF = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	440.8	$1.1 \cdot 10^3$	$3.4 \cdot 10^3$	$7.3 \cdot 10^3$	$8.5 \cdot 10^3$	$7.4 \cdot 10^3$	$7.3 \cdot 10^3$	$8 \cdot 10^3$	$6.3 \cdot 10^3$	$3.2 \cdot 10^3$	$1.2 \cdot 10^3$	511.2
2	$1.6 \cdot 10^3$	$3.6 \cdot 10^3$	$7.7 \cdot 10^3$	$1 \cdot 10^4$	$10 \cdot 10^3$	$9.1 \cdot 10^3$	$9 \cdot 10^3$	$1 \cdot 10^4$	$1.1 \cdot 10^4$	$7.1 \cdot 10^3$	$3.3 \cdot 10^3$	$1.7 \cdot 10^3$
3	$3.3 \cdot 10^3$	$6.8 \cdot 10^3$	$1.1 \cdot 10^4$	$1.1 \cdot 10^4$	$1.1 \cdot 10^4$	$9.8 \cdot 10^3$	$9.7 \cdot 10^3$	$1.1 \cdot 10^4$	$1.2 \cdot 10^4$	$9.9 \cdot 10^3$	$5.2 \cdot 10^3$	$3 \cdot 10^3$
4	$4 \cdot 10^3$	$8 \cdot 10^3$	$1.2 \cdot 10^4$	$1.1 \cdot 10^4$	$1 \cdot 10^4$	$9.5 \cdot 10^3$	$9.5 \cdot 10^3$	$1.1 \cdot 10^4$	$1.2 \cdot 10^4$	$9.5 \cdot 10^3$	$5 \cdot 10^3$	$3.3 \cdot 10^3$
5	$2.9 \cdot 10^3$	$6.3 \cdot 10^3$	$1 \cdot 10^4$	$1 \cdot 10^4$	$9.1 \cdot 10^3$	$8 \cdot 10^3$	$8.4 \cdot 10^3$	$9.9 \cdot 10^3$	$1.1 \cdot 10^4$	$6.8 \cdot 10^3$	$3.1 \cdot 10^3$	$2.1 \cdot 10^3$
6	$1.3 \cdot 10^3$	$3.5 \cdot 10^3$	$7.1 \cdot 10^3$	$8.5 \cdot 10^3$	$6.4 \cdot 10^3$	$5 \cdot 10^3$	$5.7 \cdot 10^3$	$7.9 \cdot 10^3$	$8.2 \cdot 10^3$	$3.6 \cdot 10^3$	$1.2 \cdot 10^3$	831.5
7	422	$1.3 \cdot 10^3$	$3.3 \cdot 10^3$	$3.9 \cdot 10^3$	$2 \cdot 10^3$	859	$1.7 \cdot 10^3$	$3.8 \cdot 10^3$	$3.4 \cdot 10^3$	$1.1 \cdot 10^3$	358.3	252.5
8	124.5	321.5	688.6	409.1	45.9	27.2	28.8	135.8	491.5	223.8	109.7	100.7
9	97.6	101.8	112	92.2	83.7	74.5	75	86.5	95.6	98.5	97.6	97.6

The illuminance on D at all times of the year is greater than 500 lx. However, on points A, B and C there are still some values below 500 lx. Looking at point B now, (the other luminaire is above point B and between points A and C), we have:

$$DIM1_{t,i} := \text{if}\left(0 < \frac{500 \cdot lx - BF_{t,i}}{E_{BL1}} \le 0.25, 0.25, \text{if}\left(0.25 < \frac{500 \cdot lx - BF_{t,i}}{E_{BL1}} \le 0.5, 0.5, \text{if}\left(0.5 < \frac{500 \cdot lx - BF_{t,i}}{E_{BL1}} \le 0.75, 0.75, \text{if}\left(0.75 < \frac{500 \cdot lx - B}{E_{BL1}}\right.\right.\right.\right.$$

DIM1 =

	1	2	3	4	5	6	7	8	9	10	11	12
1	0.25	0	0	0	0	0	0	0	0	0	0	0.25
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0.25	0	0	0	0	0	0	0	0	0	0.5	0.5
8	0.75	0.5	0	0.25	0.75	0.75	0.75	0.75	0.25	0.5	0.75	0.75
9	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75

Then the final illuminance on points A, B, C and D at all times of the year will be:

$IllumB_{t,i} := BF_{t,i} + DIM1_{t,i} \cdot E_{BL1}$

IllumB = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	527.2	742.1	$2.3\cdot10^3$	$4.9\cdot10^3$	$5.8\cdot10^3$	$5\cdot10^3$	$4.9\cdot10^3$	$5.4\cdot10^3$	$4.3\cdot10^3$	$2.2\cdot10^3$	784.3	574.7
2	$1.1\cdot10^3$	$2.4\cdot10^3$	$5.2\cdot10^3$	$6.9\cdot10^3$	$6.7\cdot10^3$	$6.2\cdot10^3$	$6.1\cdot10^3$	$6.8\cdot10^3$	$7.1\cdot10^3$	$4.8\cdot10^3$	$2.2\cdot10^3$	$1.1\cdot10^3$
3	$2.3\cdot10^3$	$4.6\cdot10^3$	$7.5\cdot10^3$	$7.3\cdot10^3$	$7.1\cdot10^3$	$6.6\cdot10^3$	$6.5\cdot10^3$	$7.2\cdot10^3$	$8.1\cdot10^3$	$6.6\cdot10^3$	$3.5\cdot10^3$	$2\cdot10^3$
4	$2.7\cdot10^3$	$5.4\cdot10^3$	$8\cdot10^3$	$7.2\cdot10^3$	$6.9\cdot10^3$	$6.4\cdot10^3$	$6.4\cdot10^3$	$7.2\cdot10^3$	$7.9\cdot10^3$	$6.4\cdot10^3$	$3.4\cdot10^3$	$2.2\cdot10^3$
5	$2\cdot10^3$	$4.3\cdot10^3$	$6.9\cdot10^3$	$6.8\cdot10^3$	$6.1\cdot10^3$	$5.4\cdot10^3$	$5.6\cdot10^3$	$6.7\cdot10^3$	$7.3\cdot10^3$	$4.6\cdot10^3$	$2.1\cdot10^3$	$1.4\cdot10^3$
6	882	$2.3\cdot10^3$	$4.8\cdot10^3$	$5.7\cdot10^3$	$4.3\cdot10^3$	$3.3\cdot10^3$	$3.8\cdot10^3$	$5.3\cdot10^3$	$5.5\cdot10^3$	$2.4\cdot10^3$	836.8	627
7	514.5	865.4	$2.2\cdot10^3$	$2.7\cdot10^3$	$1.4\cdot10^3$	612.6	$1.2\cdot10^3$	$2.6\cdot10^3$	$2.3\cdot10^3$	775.4	602.3	564
8	608.4	610.5	530.6	505.9	555.4	542.8	543.9	616	561.4	544.6	598.4	592.4
9	590.3	593.1	600	586.6	580.9	574.7	575	582.8	588.9	590.8	590.3	590.3

$IllumC_{t,i} := CF_{t,i} + DIM1_{t,i} \cdot E_{CL1}$

IllumC = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	582	637.9	$1.8\cdot10^3$	$3.8\cdot10^3$	$4.5\cdot10^3$	$3.9\cdot10^3$	$3.8\cdot10^3$	$4.2\cdot10^3$	$3.3\cdot10^3$	$1.7\cdot10^3$	612.3	619.1
2	850.5	$1.9\cdot10^3$	$4\cdot10^3$	$5.4\cdot10^3$	$5.3\cdot10^3$	$4.8\cdot10^3$	$4.7\cdot10^3$	$5.3\cdot10^3$	$5.6\cdot10^3$	$3.7\cdot10^3$	$1.7\cdot10^3$	871.5
3	$1.8\cdot10^3$	$3.6\cdot10^3$	$5.9\cdot10^3$	$5.7\cdot10^3$	$5.5\cdot10^3$	$5.2\cdot10^3$	$5.1\cdot10^3$	$5.6\cdot10^3$	$6.3\cdot10^3$	$5.2\cdot10^3$	$2.7\cdot10^3$	$1.6\cdot10^3$
4	$2.1\cdot10^3$	$4.2\cdot10^3$	$6.2\cdot10^3$	$5.7\cdot10^3$	$5.4\cdot10^3$	$5\cdot10^3$	$5\cdot10^3$	$5.6\cdot10^3$	$6.2\cdot10^3$	$5\cdot10^3$	$2.6\cdot10^3$	$1.7\cdot10^3$
5	$1.5\cdot10^3$	$3.3\cdot10^3$	$5.4\cdot10^3$	$5.3\cdot10^3$	$4.8\cdot10^3$	$4.2\cdot10^3$	$4.4\cdot10^3$	$5.2\cdot10^3$	$5.7\cdot10^3$	$3.6\cdot10^3$	$1.6\cdot10^3$	$1.1\cdot10^3$
6	688.6	$1.8\cdot10^3$	$3.8\cdot10^3$	$4.5\cdot10^3$	$3.3\cdot10^3$	$2.6\cdot10^3$	$3\cdot10^3$	$4.2\cdot10^3$	$4.3\cdot10^3$	$1.9\cdot10^3$	653.3	606.5
7	572.1	675.7	$1.7\cdot10^3$	$2.1\cdot10^3$	$1.1\cdot10^3$	536.7	901.4	$2\cdot10^3$	$1.8\cdot10^3$	605.4	635.7	664.2
8	693.8	700.5	531.2	565.3	652.5	642.6	643.5	699.8	608.7	649.1	686.1	681.3
9	679.7	681.9	687.3	676.9	672.4	667.5	667.8	673.9	678.7	680.2	679.7	679.7

$IllumD_{t,i} := DF_{t,i} + DIM1_{t,i} \cdot E_{DL1}$

IllumD = (lx)

	1	2	3	4	5	6	7	8	9	10	11	12
1	609.6	599.5	$1.6\cdot10^3$	$3.3\cdot10^3$	$3.9\cdot10^3$	$3.4\cdot10^3$	$3.3\cdot10^3$	$3.6\cdot10^3$	$2.9\cdot10^3$	$1.5\cdot10^3$	530.8	641.7
2	737.2	$1.6\cdot10^3$	$3.5\cdot10^3$	$4.7\cdot10^3$	$4.6\cdot10^3$	$4.2\cdot10^3$	$4.1\cdot10^3$	$4.6\cdot10^3$	$4.8\cdot10^3$	$3.2\cdot10^3$	$1.5\cdot10^3$	755.4
3	$1.5\cdot10^3$	$3.1\cdot10^3$	$5.1\cdot10^3$	$4.9\cdot10^3$	$4.8\cdot10^3$	$4.5\cdot10^3$	$4.4\cdot10^3$	$4.9\cdot10^3$	$5.5\cdot10^3$	$4.5\cdot10^3$	$2.4\cdot10^3$	$1.4\cdot10^3$
4	$1.8\cdot10^3$	$3.7\cdot10^3$	$5.4\cdot10^3$	$4.9\cdot10^3$	$4.7\cdot10^3$	$4.3\cdot10^3$	$4.4\cdot10^3$	$4.9\cdot10^3$	$5.3\cdot10^3$	$4.3\cdot10^3$	$2.3\cdot10^3$	$1.5\cdot10^3$
5	$1.3\cdot10^3$	$2.9\cdot10^3$	$4.7\cdot10^3$	$4.6\cdot10^3$	$4.1\cdot10^3$	$3.7\cdot10^3$	$3.8\cdot10^3$	$4.5\cdot10^3$	$5\cdot10^3$	$3.1\cdot10^3$	$1.4\cdot10^3$	945
6	596.9	$1.6\cdot10^3$	$3.3\cdot10^3$	$3.9\cdot10^3$	$2.9\cdot10^3$	$2.3\cdot10^3$	$2.6\cdot10^3$	$3.6\cdot10^3$	$3.7\cdot10^3$	$1.7\cdot10^3$	566.3	618.8
7	601	585.7	$1.5\cdot10^3$	$1.8\cdot10^3$	934	511.8	781.3	$1.7\cdot10^3$	$1.6\cdot10^3$	524.8	621.4	692.7
8	683.8	724.2	553.6	595.1	647.9	639.4	640.1	688.9	632.7	679.6	677	672.9
9	671.5	673.4	678.1	669	665.2	661	661.2	666.4	670.6	671.9	671.5	671.5

$IllumA_{t,i} := AF_{t,i} + DIM1_{t,i} \cdot E_{AL1}$

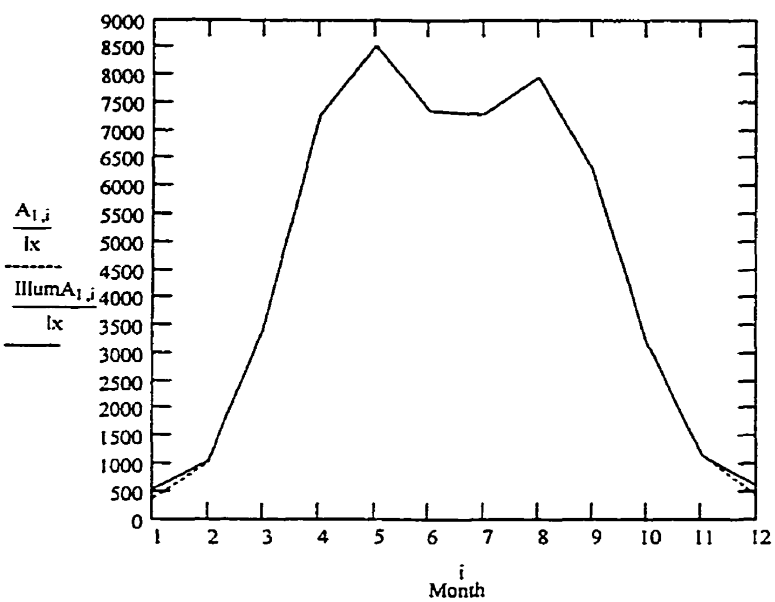
IllumA =

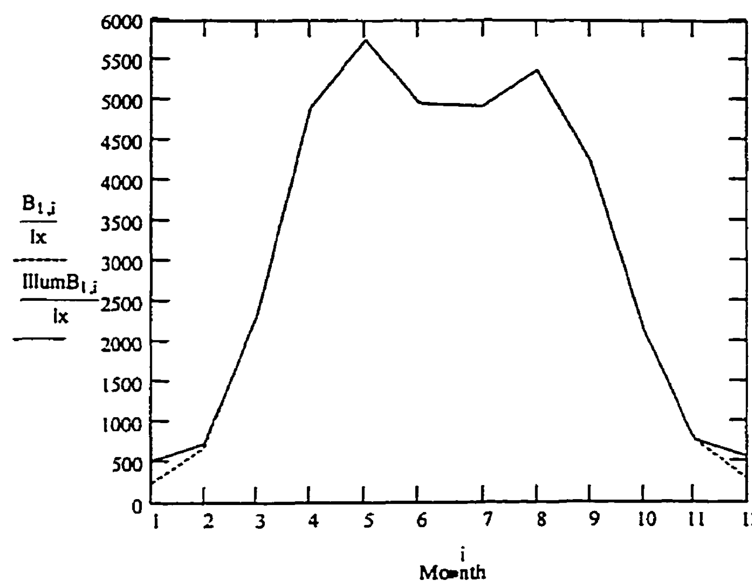
	1	2	3	4	5	6	7	8	9	10	11	12
1	537.9	$1.1\cdot10^3$	$3.4\cdot10^3$	$7.3\cdot10^3$	$8.5\cdot10^3$	$7.4\cdot10^3$	$7.3\cdot10^3$	$8\cdot10^3$	$6.3\cdot10^3$	$3.2\cdot10^3$	$1.2\cdot10^3$	608.3
2	$1.6\cdot10^3$	$3.6\cdot10^3$	$7.7\cdot10^3$	$1\cdot10^4$	$10\cdot10^3$	$9.1\cdot10^3$	$9\cdot10^3$	$1\cdot10^4$	$1.1\cdot10^4$	$7.1\cdot10^3$	$3.3\cdot10^3$	$1.7\cdot10^3$
3	$3.3\cdot10^3$	$6.8\cdot10^3$	$1.1\cdot10^4$	$1.1\cdot10^4$	$1.1\cdot10^4$	$9.8\cdot10^3$	$9.7\cdot10^3$	$1.1\cdot10^4$	$1.2\cdot10^4$	$9.9\cdot10^3$	$5.2\cdot10^3$	$3\cdot10^3$
4	$4\cdot10^3$	$8\cdot10^3$	$1.2\cdot10^4$	$1.1\cdot10^4$	$1\cdot10^4$	$9.5\cdot10^3$	$9.5\cdot10^3$	$1.1\cdot10^4$	$1.2\cdot10^4$	$9.5\cdot10^3$	$5\cdot10^3$	$3.3\cdot10^3$
5	$2.9\cdot10^3$	$6.3\cdot10^3$	$1\cdot10^4$	$1\cdot10^4$	$9.1\cdot10^3$	$8\cdot10^3$	$8.4\cdot10^3$	$9.9\cdot10^3$	$1.1\cdot10^4$	$6.8\cdot10^3$	$3.1\cdot10^3$	$2.1\cdot10^3$
6	$1.3\cdot10^3$	$3.5\cdot10^3$	$7.1\cdot10^3$	$8.5\cdot10^3$	$6.4\cdot10^3$	$5\cdot10^3$	$5.7\cdot10^3$	$7.9\cdot10^3$	$8.2\cdot10^3$	$3.6\cdot10^3$	$1.2\cdot10^3$	831.5
7	519.1	$1.3\cdot10^3$	$3.3\cdot10^3$	$3.9\cdot10^3$	$2\cdot10^3$	859	$1.7\cdot10^3$	$3.8\cdot10^3$	$3.4\cdot10^3$	$1.1\cdot10^3$	552.5	446.7
8	415.8	515.7	688.6	506.2	337.2	318.5	320.1	427.1	588.6	418	401	392
9	388.9	393.1	403.3	383.5	375	365.8	366.3	377.8	386.9	389.8	388.9	388.9

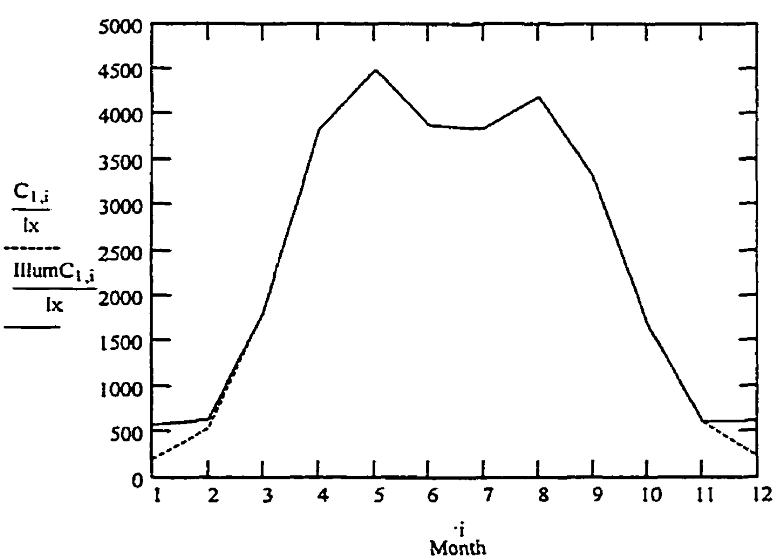
lx

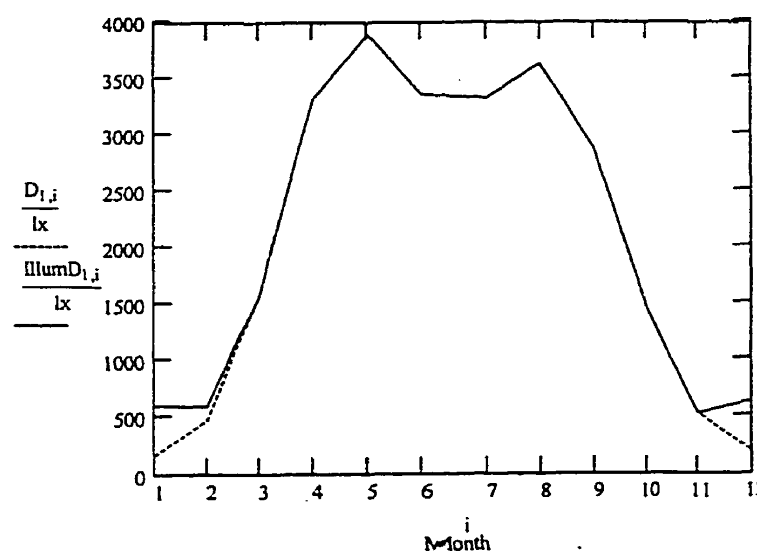
Now in all cases the illuminance is above 500lx at all times of the year, except for some winter afternoon hours at point A.

A graphical visualization is presented in the following figures. The illuminance on points A, B, C and D is shown for 9am of the identical day of each month only with natural daylight (dashed line) and with dimming of electric lights (solid line).









ESTIMATION OF ENERGY SAVINGS

Each lamp needs 196 input Watts and a ballast with 15 W is needed for each pair of lamps. Thus for each luminaire (4 lamps) the input Watts are 4x60 + 2x15 = 270 W. For an office space with no daylighting control or on/off operation of electric lights, the annual energy consumption due to electric lighting will be:

luminaire input Watts* number of luminaires* hours per day* 360 days

$$En_o := 270 \cdot W \cdot 2 \cdot 8hr \cdot 360 \qquad En_o = 5.599 \times 10^9 J$$

With the Vision Control window and the dimming of the lights, the energy consumed in a year will be:

$$En := 30 \cdot \sum_{t=1}^{8} \sum_{i=1}^{12} \left(DIM1_{t,i} + DIM2_{t,i}\right) \cdot 270 \cdot W \cdot hr \qquad En = 7.144 \times 10^8 J$$

So the energy saved will be: $En_o - En = 4.884 \times 10^9 J$ or $\frac{En_o - En}{En_o} = 0.872$ or 87.2%