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

Andreas K. Athienitis, Professor, Centre for Building Studies, athiena@alcor.concordia.ca
Athanassios Tzempelikos, Research Assistant, Concordia University, Montreal, agtzemb@alcor.concordia.ca

ABSTRACT

This paper presents a methodology for detailed lighting/daylighting numerical simulation of an office space with an advanced window system and calculation of dimming levels for electric lights. The particular system considered is a double-glazed low-emissivity window with motorized highly reflective blinds between the two glazings installed in an outdoor test-room and operated by a custom-built computerised building automation system. The daylight transmittance equations for the window system were determined from experimental measurements. A major requirement for on-line control is the automatic determination of the blind tilt angle required in order to avoid glare and simultaneously allow the maximum possible amount of daylight in the room. Numerical simulations indicate energy savings of over 70% in electricity consumption for lighting.

INTRODUCTION

Utilization 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 realized during the cooling season, when reduction of internal heat gains due to electric lighting results in a corresponding reduction of cooling energy consumption.

The concept of dynamic building envelope technologies introduces a potential for higher quality work environment as well as energy-efficient solutions. Innovative daylighting systems aim to increase daylight levels and improve the daylight uniformity within a space, while controlling sunlight and reducing glare and discomfort for the occupants (*Lorenz, 2000, Beck, 1999*). Simultaneous control of electric lighting systems and building envelope conventional components can minimize energy use (*Vartiainen, 1999*). Predictive control algorithms, can determine the optimal operation of all HVAC components and building envelope systems in order to achieve annual minimization of energy consumption (due to lighting/heating/cooling) while maintaining good human comfort (*Lee, 1995, 1998, Scheatzle, 1990*).

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-facing facades of buildings. Shading devices can be multi-purpose: blocking direct sun and solar gains during the cooling season, allowing the maximum amount of daylight and solar gains during the heating season, controlling the sunlight by diffusing it into the space without causing glare on clear days, while, at the same time, transmitting all the available daylight on overcast days. Human control of moving shading devices is not reliable and causes a constant disruption for the occupants if optimum results are to be achieved. In modern offices, the need for efficient automation systems is greater than ever and motorized shading devices are an attractive option.

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 (*Molina, 2000*). 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*).

This paper presents a methodology for detailed lighting/daylighting numerical simulation of an office space with an advanced window system and calculation of dimming levels for electric lights so as to optimize utilization of daylight and minimize electricity consumption. The particular system considered is a double-glazed low-emissivity window with motorized highly reflective blinds between the two panes installed in an outdoor test-room and operated by a custom-built computerised building automation system. The daylight transmittance equations for the window system were determined from experimental measurements. A technique for detailed simulation of the illuminance level on the

work plane area is then presented together with a dimming control algorithm for a typical office space.

EXPERIMENTAL MEASUREMENTS AND RESULTS

The experiments were performed in an outdoor test-room in Montreal. The interior dimensions of the test-room are 2.3 m wide × 2.7 m wide × 2.4 m high and the window system is integrated on the façade facing 10 degrees east of south (Fig. 1).

Fig. 1. Outside view of the test-room with the window (daylight and solar radiation sensors are mounted just beside the window).

The window ("Vision Control window"), provided by Unicel Inc., is double-glazed with a low-emissivity coating and highly reflective louvers integrated between the two panes; its dimensions are 1.08 m ×1.08 m. The motorized louvers are made of extruded aluminium, hollow-chambered profile with overlap. They are 35mm wide and 6mm thick at the centre. They can rotate in both directions (180°).

Several solar radiation and daylight sensors were employed to measure solar radiation and its visible portion respectively. Two were mounted on the wall just beside the window (Fig. 1) to measure the solar radiation and daylight incident on the window. There is no single widely used procedure for measuring the transmittance of such non-homogeneous shading devices. A method presented by *Aleo (1994)* is a typical approach. In this study the sensors were mounted at the centre of the inside surface of the window. A detailed investigation of the illuminance uniformity over the whole window area showed that, the daylight uniformity ratio (maximum/minimum value) was less than 110%, taking its maximum value at the centre of the window area. Another movable daylight sensor was installed in the room at a height 0.85m from the floor, to measure the illuminance level at different locations on the work plane. Data were collected for five months, from July 2000 to November 2000.

A customised data acquisition and control (building automation) program was developed in C++ and employed in this project. It was designed to offer the user several options in the control of the blinds and the heating/cooling system. Data were usually sampled every 6 seconds and averaged every 6 minutes. 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 obtain an accurate characterization of the transmittance properties of the window system.

Transmittance Of The Window And Shading Device

The transmittance equation for the window was determined as a function of sky conditions, blind tilt angle (β) and angle of incidence (θ) (see Fig. 2). Two sky conditions are considered: (i) overcast sky and (ii) the clear sky. Because the two types of days (clear and overcast) cannot be perfectly reproduced, measurements were taken for a large number of days falling into these categories and then statistical analysis of the collected data gave average values for the transmittance on a typical cloudy and on a sunny day.

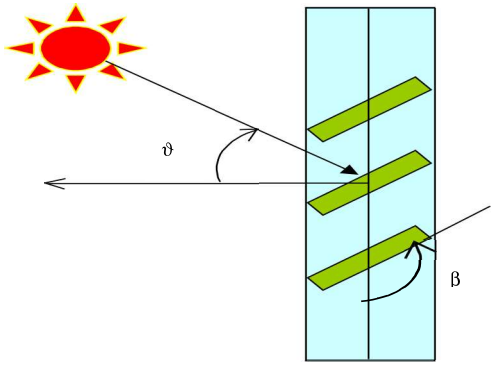

Fig. 2. Schematic of window indicating blind tilt angle, β, and angle of incidence, θ.

The angle of incidence is chosen as a parameter of the transmittance equation so that it can then be employed for any window orientation and any location. The transmittance value for a certain blind tilt angle and angle of incidence is found by dividing the illuminance measured on the inside surface of the window by the value measured by the exterior sensors. Figures 3-6 show the visible transmittance

(τ_v) as a function of blind tilt angle (β) and angle of incidence (θ) for both overcast and clear days.

For overcast days, the tilt angle has a strong effect on daylight transmittance (Fig. 3). The curve reaches a maximum at about β=60° for all angles of incidence. For this blind tilt angle, the maximum value is τ_v=38.2%, for θ=27°. The incidence angle has a negligible effect on τ_v, since there is only diffuse daylight; this can also be observed from Fig. 4. These curves can be expressed by an equation independent of θ (only a function of β). Using advanced analytical regression techniques, the following equation was obtained (regression coefficient = 0.99):

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

For clear sky, the incidence angle has a significant effect on transmittance (Figures 5, 6). The visible transmittance is higher for smaller incidence angles and there is a minimum around θ = 45°. The maximum value (τ_v=55%) is measured for β = 78° and θ=15°. Using multivariate regression techniques the following general equation was obtained (regression coefficient = 0.99):

$$\tau_v^{clear}(\beta,\theta) = 0.55 \cdot e^{\frac{(\beta-80)^2}{1900}} \cdot (-4.917 \cdot 10^{-7} \cdot \theta^4 + 0.00009 \cdot \theta^3 - 0.00567 \cdot \theta^2 + 0.13 \cdot \theta - 0.00437) \quad (2)$$

The above equation consists of two terms: the first term describes the effect of blind tilt angle (it is a normal distribution approximation with the maximum of the curve at β=80 degrees as shown in Fig. 5). The second term describes the effect of θ on the transmittance: it is approximated by a 4th-degree polynomial curve (Fig. 6).

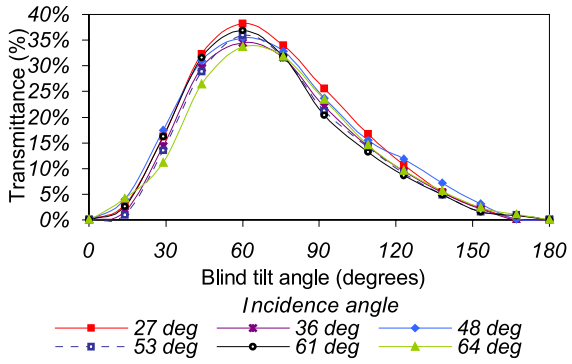

Fig. 3. Daylight transmittance as a function of β for several solar incidence angles, overcast day.

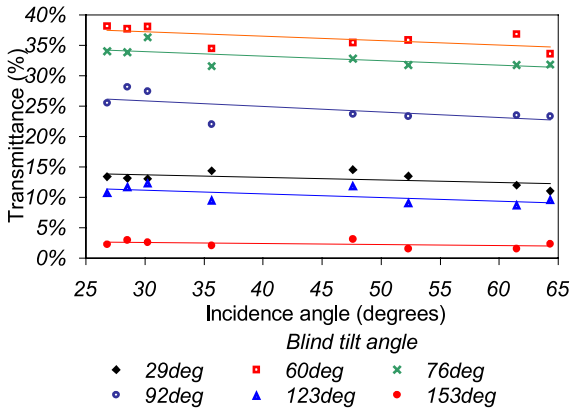

Fig. 4. Daylight transmittance as a function of θ for various blind tilt angles, overcast day.

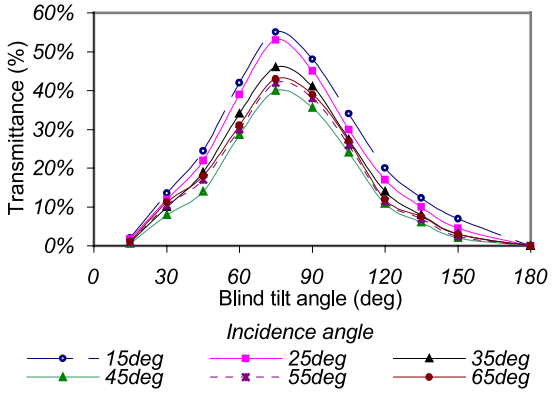

Fig. 5. Daylight transmittance as a function of β for various solar incidence angles, clear day.

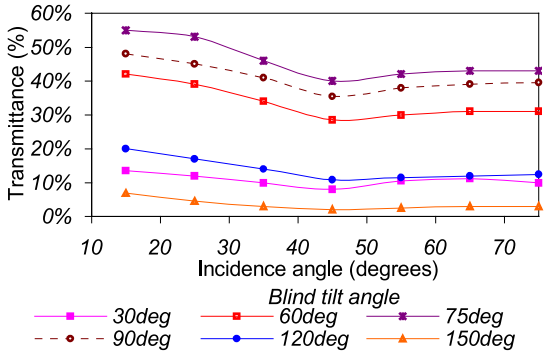

Fig. 6. Daylight transmittance as a function of θ for various blind tilt angles, clear day.

SIMULATION METHODOLOGY

Given the transmittance of a window with a controlled shading device as a function of angle of incidence, shading device position and sky conditions, a simulation of an office space with such a window may be performed. The technique developed determines first the optimum tilt angle of the blinds in order to transmit the maximum possible

amount of daylight without causing glare (by eliminating beam radiation) while allowing the maximum possible view outside. Then, it determines the illuminance due to daylight at several (3-4) points on the work plane (which is assumed to be 0.8 m above the floor) for representative days in each month, once every hour, from 9 am to 5 pm (typical working hours for an office). The dimming levels for the artificial lighting are then determined in order to provide the balance of light required to achieve the required total illuminance levels. Finally, it calculates the energy savings due to electrical lighting from simultaneous control of the blinds and dimming of the lights.

The main input variables in the program are the day number in the year (n) and the solar time (t). Here we considered a 5×5×3m office space located in Montreal, with a 2×4m Vision Control window on the façade facing 10° east of south, with no obstructions and ground reflectance equal to 20%. The reflectance of the floor is assumed to be 30%, the ceiling reflectance 80% and the reflectance of all sidewalls 70%. The angle of incidence is first calculated for every hour of each representative monthly day. The next step is to calculate the illuminance incident on the window. At this point sky conditions must be selected.

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 a concern. In order to allow better view outside and also transmit the maximum possible amount of daylight in the room, the optimum tilt angle is selected, in this case $\beta_{opt}^{diffuse}= 75°$ ($\tau_v \approx 30\%$).

The daylight from the sky is equal to the horizontal illuminance multiplied by the view factor between the sky and the window $F_{w\text{-}sky}$, (0.5 for vertical window). The daylight from the ground is equal to the horizontal illuminance multiplied by the ground reflectance (ρ_g) times the view factor between the ground and the window $F_{w\text{-}gr}$ (0.5). The daylight incident on the window is the sum of these two terms:

$$E_w = E_h \cdot F_{w\text{-}sky} + E_h \cdot F_{w\text{-}gr} \cdot \rho_g \quad (3)$$

The horizontal illuminance under a CIE overcast sky (Murdoch 1985) on a certain day n and time t may be expressed as (lx):

$$E_h^{ov}(n,t) = 1000 \cdot (0.3 + 21 \cdot \sin(\alpha(n,t)) \quad (4)$$

Where α is solar altitude. Thus the daylight incident on the window on an overcast day at time t will be:

$$E_w^{ov}(n,t) = 500 \cdot (0.3 + 21 \cdot \sin(\alpha(n,t)) \cdot (1+\rho_g) \quad (4a)$$

The daylight transmitted in the room is equal to:

$$E_{overxast}(n,t) = E_w^{ov}(n,t) \cdot \tau_v^{diffuse}(\beta_{opt}^{diffuse}) \quad (5)$$

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 is given by:

$$E_{hsky}(n,t) = 800 + 15500 \cdot [\sin(a(n,t))]^{1/2} \quad (6)$$

The solar horizontal illuminance is:

$$E_{hsun}(n,t) = E_o \cdot f(n) \cdot e^{-c \cdot m(n,t)} \cdot \sin(a(n,t)), \quad (7)$$

where:

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

$$f(n) = 1 + 0.033 \cdot \cos(360 \cdot n/365)$$

is a correction factor to account for the elliptical shape of earth's orbit around the sun, c is the optical atmospheric extinction coefficient (equal to 0.21 for a clear day), and

$m(n,t) = 1/\sin(a(n,t))$ is the relative optical air mass. The total horizontal illuminance is given by:

$$E_h^{clear}(n,t) = E_{sky}(n,t) + E_{hsun}(n,t) \quad (8)$$

The daylight incident on the window from the ground $E_{wgr}(n,t)$ and from the sky $E_{wsky}(n,t)$ are given by:

$$E_{wgr}(n,t) = F_{w\text{-}gr} \cdot \rho_g \cdot E_h(n,t) \quad (8a)$$
$$E_{wsky}(n,t) = F_{w\text{-}sky} \cdot E_{hsky}(n,t) \quad (8b)$$

The daylight incident on the window directly from the sun is given by:

$$E_{wsun}(n,t) = E_o \cdot f(n) \cdot e^{-c \cdot m(n,t)} \cdot \cos(\theta(n,t)) \quad (8c)$$

Thus the total daylight incident on the window on a clear day may be expressed as follows:

$$E_w^{clear}(n,t) = E_{wgr}(n,t) + E_{wsky}(n,t) + E_{wsun}(n,t) \quad (8d)$$

In the case of clear sky, it is desired 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 we are only interested in the solar altitude. Fig. 7 shows two adjacent blinds in a horizontal position

(β=90°) and at another position at an angle β. The distance between the blinds and the width of each blind are both equal to r. For a random position of the blinds, a direct ray can enter the room (without reflection on the blinds) only for solar altitudes between 0° and α°. In other words, for a certain solar altitude (time), the minimum blind tilt angle that must be set to prevent direct sunlight from coming into the room is the angle β shown in Fig. 7. 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) and second, to allow better view to the outside. Calculating β as a function of solar altitude α from the geometry of Fig. 7 will give the optimum tilt angle for any time and day on clear days. 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, for the hours that α>45°, the blinds will be set at β=90° to maximize view field. For all the other cases the calculations must be performed. Considering triangle ABC we obtain:

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

Solving this equation for β, we find:

$$\beta_{opt}^{clear}(n,t) = 180° - 2 \cdot \alpha(n,t) \qquad (9a)$$

The optimum blind tilt angle to block beam radiation is selected as follows:

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

else $\beta_{opt}^{clear}(n,t)=180° - 2 \cdot \alpha(n,t)$ (9b)

The daylight transmitted in the room on a clear day at any time and day is:

$$E_{clear}(n,t)= E_w^{clear}(n,t) \cdot \tau_v^{clear}(n,t) \qquad (9c)$$

Luminous Exitances And Illuminance On The Work Plane

The window interior surface is considered as a diffuse luminous source emitting daylight towards all directions in the room. Although this is true for blind tilt angles near 90° (horizontal), it causes some 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 thetransmitted daylight is reflected towards the work plane, the floor and the sidewalls.

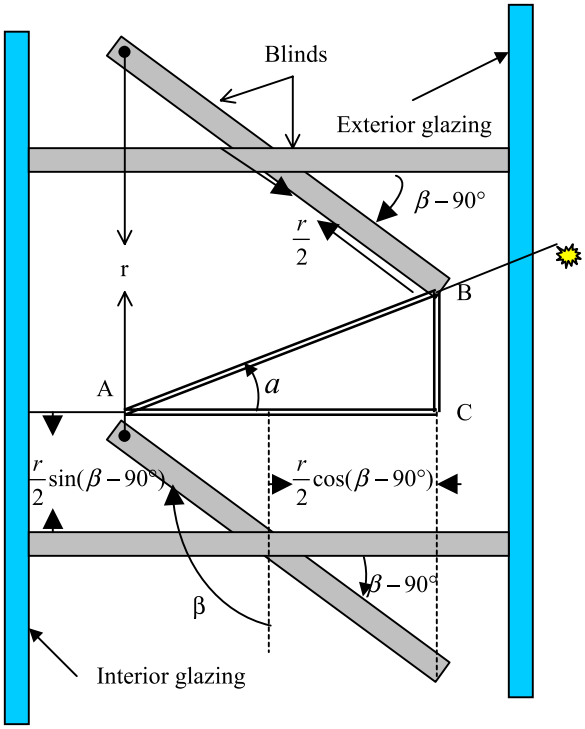

Fig. 7. Cross-section of the window for the calculation of angle β to prevent glare on clear days.

The room is first modelled by 7 surfaces (i=1..7): the window, the wall containing the window, the floor, the ceiling, the back wall and the two sidewalls. Only the window surface has an initial luminous exitance (the transmitted daylight).

The final luminous exitances of all interior surfaces after multiple reflections in the room are next calculated based on radiosity analysis. 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. Using form factors, the final luminous exitance of each interior surface (M_i) is determined by:

$$M_i = M_{oi} + \rho_i \cdot \Sigma M_j \cdot F_{ij} \qquad (10)$$

where ρ is the surface reflectance. This system of equations may be written in matrix form as follows:

$$\boldsymbol{M_o} = \boldsymbol{(I-T)} \cdot \boldsymbol{M}, \qquad (10a)$$

where $\boldsymbol{M_o}$ is the initial luminous exitance matrix, $\boldsymbol{I}$ is the 7x7 identity matrix and $\boldsymbol{T}$ is a matrix whose

elements are given by $T_{ij} = \rho_i \cdot F_{ij}$.

The matrix of the final luminous exitances of the interior surfaces is calculated from:

$$\boldsymbol{M}(n,t) = (\boldsymbol{I}-\boldsymbol{T})^{-1} \cdot \boldsymbol{M_o}(n,t) \quad (11)$$

The next step is to select representative points on the work plane and calculate the illuminance. Four points are selected (A, B, C and D) on the work plane 2.5 m 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.
In order to compute the illuminance on the selected points, the configuration factors need to be determined between each of the points and all interior surfaces of the room. The configuration factor c_{SI-A} is defined as the ratio of the illuminance at a differential area (point A) produced by the flux received directly from a surface (S_I) due to the luminous exitance of S_I. The illuminance at each point for all days and times is given by (in matrix form):

$$\boldsymbol{E}_{A,B,C,D}(n,t) = \sum M_i(n,t) \cdot C_{Ai,Bi,Ci,Di} \quad (12)$$

Fig. 8 shows the illuminance profile of the room (at points A, B, C, D) on a clear and on an overcast day in January.

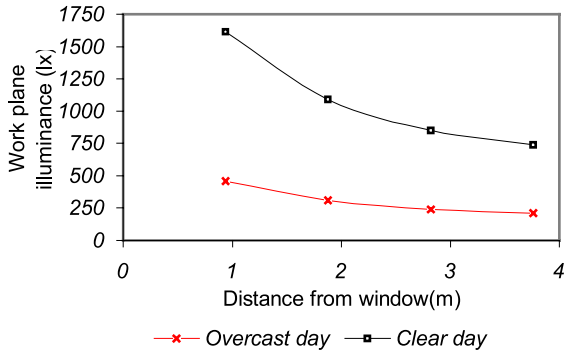

Fig. 8. Illuminance distribution on the work plane, on a typical overcast and clear day in January (10am).

On clear days allows plenty of diffuse daylight is transmitted into the room, without causing glare, and even at 4 m from the window there are more than 750 lx on the work plane. On overcast days artificial lighting is necessary.

SIMULATION RESULTS

The blinds are automatically operated, and based on the above results, electrical lights are automatically dimmed in order to improve the illuminance distribution in the office and provide the necessary additional illumination to reach a pre-selected setpoint (500lx). The luminaires selected for this simulation were chosen based on standard sizing methods (coefficient of utilization, Murdoch 1985). Each luminaire consists of four 60 W rapid start fluorescent lamps with 3850 initial lumens per lamp. The required number of luminaires is two, in order to ensure 500 lx on the working plane. The position of the two luminaires 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). It is assumed that the dimming is not continuous, but it can be applied at four possible levels: 25%, 50%, 75% and 100% of maximum output. Knowing the illuminance at the four points due to daylight, the additional illuminance required to reach 500lx on all points is calculated.

First, L_2 is dimmed (which is deeper in the room) and then, depending on the new illuminance level on points A and B, L_1 is dimmed at the optimum level. The dimming level for both L_1 and L_2 is calculated for all the working hours of the year in matrix form. These calculations are performed for both clear and overcast days. Representative results are shown in figures. On overcast days, this dimming strategy improves significantly the illuminance distribution in the office and ensures that there are always more than 500 lx at each of the four points (Fig. 9, Fig. 10). On clear days, when there is not enough daylight after 3pm, the problem is eliminated and the illuminance distribution is also improved (Fig. 11, Fig. 12).

The results from the calculations of the dimming levels throughout the year are the following: on clear days, L_1 and L_2 are off except for the time between 4 pm and 5 pm in the evening, when L_1 is dimmed at 75% and L_2 (which is deeper in the room) is 100% on. This happens for all months of the year except December, when the lights are dimmed during all the working hours of the day. On overcast days, L_1 is dimmed at all times in winter and only from 4pm to 5pm in the other months, but L_2 needs to be dimmed during all months, as shown in Fig. 13.
On overcast days, L_1 is kept off during 65% of the working hours and L_2 is kept off during 19.4% of the working hours of the year.
On clear days, L_1 is kept off during 73.1% of the working hours and L_2 is kept off during 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.

Comparing with an office space where neither dimming of the lights nor on/off operation is

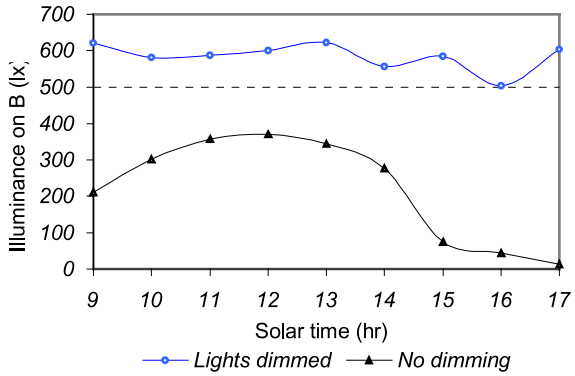

Fig. 9. Horizontal illuminance at point B on a typical overcast day in December (no dimming indicates lights off – only daylight present).

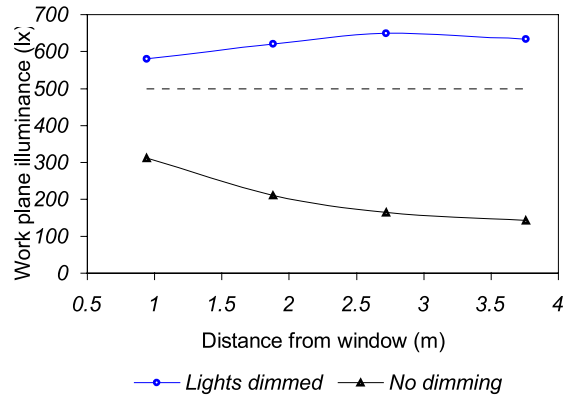

Fig. 10. Illuminance on the work plane at 9am on an overcast day in December (lights are dimmed at 75% (L_2) and 25% (L_1); no dimming indicates lights off).

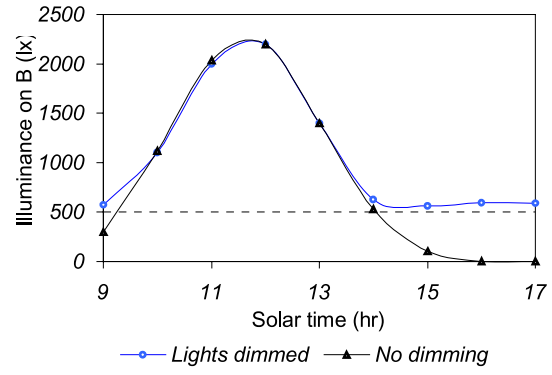

Fig. 11. Horizontal illuminance on point B on a typical clear day in December. Lights remain off from 9:30am to 2:00pm (no dimming indicates lights off).

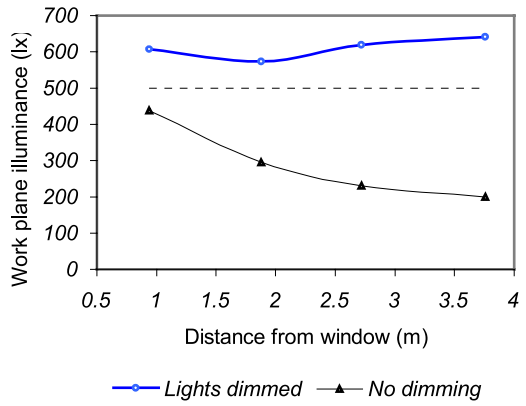

Fig. 12. Illuminance on the work plane at 9am on a typical clear day in December (L_1 is dimmed at 75% after 4pm and L_2 at full output after 2pm; no dimming indicates lights off).

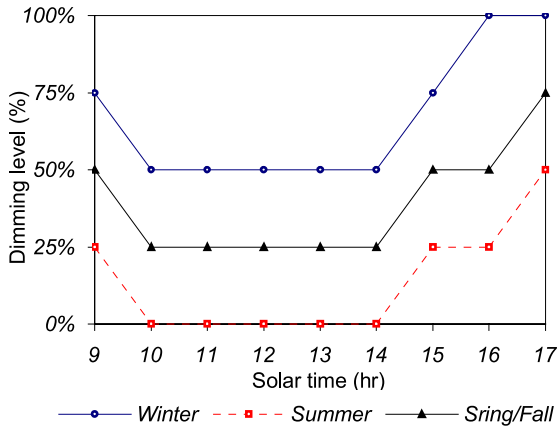

Fig. 13. Dimming levels of L_2 (3.76m from the window) during all seasons of the year.

available (lights are on at 100% output during all the working hours of the year), the energy savings due to electric lighting using the window system and the dimming methodology presented above reach 76.2% for overcast days and 87.6% for clear days.

CONCLUSION

This paper presented a methodology for detailed lighting numerical simulation of an office space with an advanced window system incorporating motorized reflective blinds between the two panes. Based on experimental measurements in an outdoor test-room, the daylight transmittance equations for the window system were determined as a function of sky conditions, blind tilt and angle of incidence. Given the transmittance equations for the window and the blind tilt angle for avoiding glare, the program then calculates the horizontal illuminance on selected

points on the work plane. Then, knowing all the illuminance values due to daylight at the required times, and choosing a required illuminance level on the work plane, the dimming factors needed are computed for the pre-selected luminaires. Finally the computer program determines energy savings from dimming of the lights.

The energy savings due to using the window system and the dimming methodology presented may exceed 70% for overcast days and 85% for clear days. Also, proper control of the blinds provides protection against direct solar radiation and glare.

In the case of partly cloudy days (when there are intervals of direct sunlight), the building automation system will determine the type of the sky conditions at regular times, based on the readings of an exterior sensor. In this case, frequent movement of the blinds must be prevented for psychological reasons (*Vine, 1998*), which should always be taken into account when dealing with advanced shading devices and innovative daylighting components.

Another factor to be investigated in the future is the impact of ground reflectance on the transmittance of the window, expected to be important when there is snow cover. However, in office buildings located in cities without frequent snow cover, this effect is not expected to be significant. Finally, although transmittance was expressed as a function of incidence angle in order to generalize the results, there is a surface azimuth angle effect, that although partly considered needs to be further studied.

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