INVESTIGATION OF LIGHTING, DAYLIGHTING AND SHADING DESIGN OPTIONS FOR NEW CONCORDIA UNIVERSITY ENGINEERING BUILDING

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ABSTRACT

This paper presents a simulation study of façade design options for the new Engineering building of Concordia University in Montreal. Optimal shading and daylighting configurations are determined, based on hourly illuminance distributions calculated with a radiosity-based simulation method. Simulations include the estimation of the performance of motorized shading devices in conjunction with controllable electric lighting systems using two lighting control options. Hourly simulations were also performed for an atrium façade facing southwest. Other daylighting concepts are also considered, such as natural illumination of corridors adjacent to the perimeter offices. Simulation results showed that, using an optimum combination of shading devices and controllable electric lighting systems, the energy savings in the perimeter spaces due to reduction in electricity consumption for lighting may exceed 80%. Moreover, the illuminance conditions are significantly improved, resulting in a high quality and pleasant visual environment.

INTRODUCTION

Innovative daylighting systems and dynamic building envelope elements have recently been employed to create a high quality indoor environment and control solar gains. At the same time, significant savings in electricity consumption for heating, cooling and lighting are realized if the above systems operate optimally [1]. Advanced windows, complex fenestration systems and new types of shading devices are being produced and studied to be integrated in the building envelope [2].

Shading provision should be considered as an integral part of fenestration system design, especially for facades with high solar gains. Shading devices may control solar gains, block direct sunlight and transmit diffuse daylight in the room [3], eliminating glare and high contrast and creating a pleasant luminous environment. Fixed shading devices are usually employed in the building envelope to exclude solar radiation in the summer and admit it during the winter. However, they also block a significant amount of diffuse daylight and they are not effective under cloudy skies. On the other hand, movable shading devices can be adjusted to changing outdoor conditions. These devices can be either manually operated or motorized, operated by the building automation system. Human control of movable shading devices is not reliable and may cause a constant disruption for the occupants. Dynamic control of motorized shading devices, fenestration systems, electric lighting and HVAC system components may lead to minimization of energy consumption for lighting, heating and cooling while maintaining good thermal and visual comfort under continuously changing outside conditions [1].

SHADING DESIGN OPTIONS

The 17-stotey high building has a large perimeter area (floor area 53000m^2) and its two main facades face southwest and southeast, respectively. The optimum glazing (vision) faction of the curtain wall façade was determined to be two thirds, based on heating and cooling load calculations as well as daylighting. These two facades receive high amounts of solar radiation during the year and appropriate shading is essential to redirect/diffuse beam sunlight and prevent from overheating in perimeter spaces. The type of glazing chosen for the façade was clear (R-value=0.67 RSI), in order to maximize daylight penetration in perimeter spaces. Perimeter spaces include offices (4x4x4.25m high), labs and an atrium on the southwest façade of the building.

The types of shading devices considered in the simulation are: (i) motorized reflective venetian blinds integrated in the windows, (ii) internal roller blinds with transmittance in the range 10%-30%, (iii) a translucent glazing unit with honeycomb insulation between glazings and (iv) combinations of the above. The choice of the optimum type and transmittance of shading devices is an optimization problem. It has an impact on heating/cooling energy consumption, peak loads and visual comfort. The major parameters considered in the decision analysis are: visual and solar transmittance, thermal resistance, visual comfort, reduction of glare and cooling load, privacy, control issues, reflectivity, appearance and cost. A combination of shading devices, which is shown to be optimal, is depicted in Fig. 1.

SIMULATION METHODOLOGY

Detailed hourly simulations were performed in order to calculate the illuminance distribution in perimeter offices, for all the shading options and for both clear and overcast days in the year. First, the solar angle of incidence $\theta(n,t)$ and the incident daylight $E(n,t)$ on each façade are computed as a function of day number (n) and solar time (t), based on CIE clear and overcast sky models [4]. Figure 2 shows the available daylight incident on the southwest façade of the building during the year at solar noon (Montreal, 45^0 N latitude). The transmitted daylight into the room is calculated next. The amount of transmitted daylight depends on the type of glazing and shading device used. For all cases, it is assumed that direct (beam) sunlight is not allowed to enter the room; shading devices block direct light and re-direct it or diffuse it into the space. In the case of motorized venetian blinds, their transmission characteristics were determined as a function of n and t [5]. They are optimally operated by the building automation system to block all direct sunlight during clear days, while allowing the maximum possible amount of daylight during overcast days. For the case of the interior roller blind, the transmittances of the window and the roller blind have to be calculated separately. The diffuse transmittance of the window is assumed fixed [6]. The roller blind transmittance (τ_{b}) is assumed constant. Values from 10% to 30% were considered. The transmittance of the translucent glazing is approximately constant (50%). Figure 3 shows the beam transmittance for the different shading options during a clear day.

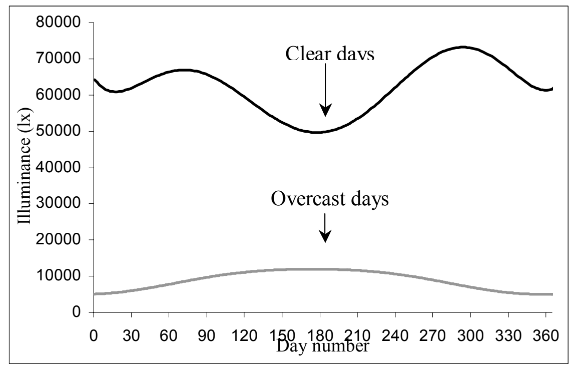

Fig. 2. Daily illuminance (at noon) due to daylight on southwest façade during the year.

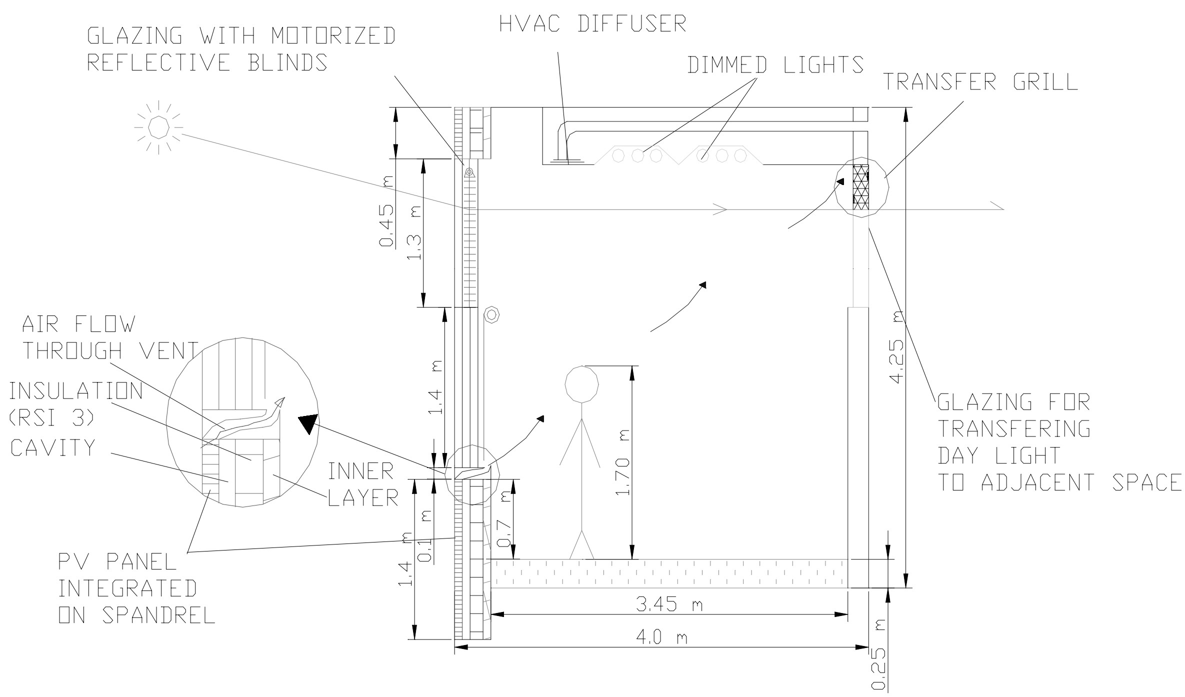

Fig. 1. The multifunctional façade with one daylighting - shading option for typical perimeter office.

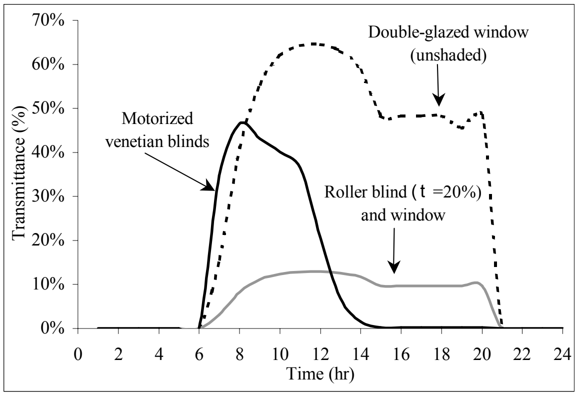

Fig. 3. Transmittance of shading devices (and window) as a function of time (July 15th).

The daylight transmitted into the room is equal to:

$$G(n,t)=E(n,t)\cdot\tau(n,t) \quad (1)$$

where $\tau(n,t)$ is the effective transmittance of the window and shading device. The illuminance distribution on the work plane after multiple reflections in the room may then be calculated, using a radiosity-based analysis [7].

If only one shading device is used, the room interior is modeled as a seven-surface enclosure (six walls and one window, $i=1..7$). The six walls are simulated as perfectly diffuse sources, with the following reflectances: 30% (floor), 70% (walls) and 5% (window). The roller blind is also modeled as a diffuse surface. In this case, the roller blind is the only initial luminous source and diffuse light is reflected multiple times between all room interior surfaces. The final illuminance on the work plane is computed as described by Athienitis and Tzempelikos (2002), after calculating view factors, final luminous exitance of all surfaces [8], and configuration factors for representative points on the work plane. The same approach is followed for the translucent glazing.

However, for the case of the motorized venetian blinds, it was found that this kind of system does not transmit daylight uniformly into the room as a diffuse luminous source. Instead, there are directional effects due to the blinds' inclination (to block sunlight) and their high reflectivity (85%). Experimental measurements showed that almost 35% of the transmitted daylight is reflected horizontally ($\pm10^0$ deviation), 25% is reflected downwards (mainly towards floor) and at least 35% is reflected towards the ceiling, as shown in Figure 4.

This directional distribution of transmitted daylight can change the illuminance distribution on the work plane significantly. Therefore, it was taken into

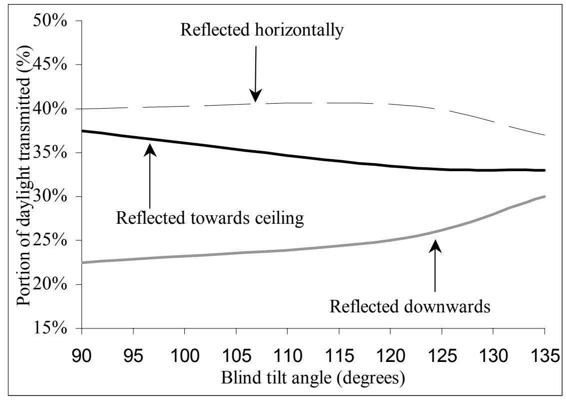

Fig. 4. Directional distribution of transmitted daylight through motorized venetian blinds, for different blind tilt angles.

account when calculating the illuminance in the room by increasing the luminous exitances of the floor, the back wall and the ceiling by the appropriate amount.

For the case where more than one shading device is used (combinations), the room is modeled as an eight-surface enclosure (six walls and two windows) with two initial luminous sources (the window with the motorized venetian blinds and the roller blind). The top part of the window can be either motorized venetian blinds or the honeycomb translucent glazing (1.3m high) and the bottom part of the window (1.4m high) is always shaded by a roller blind. The same approach as before is followed and all the surfaces are assumed diffuse, except for the window with the venetian blinds. Illuminance distributions were determined for every hour in the year, considering all the above shading options, for all perimeter spaces, for both clear and overcast days. Fig. 5 shows typical results. The illuminance with the translucent glazing is not included in the graph because its values are very high (15000 lx).

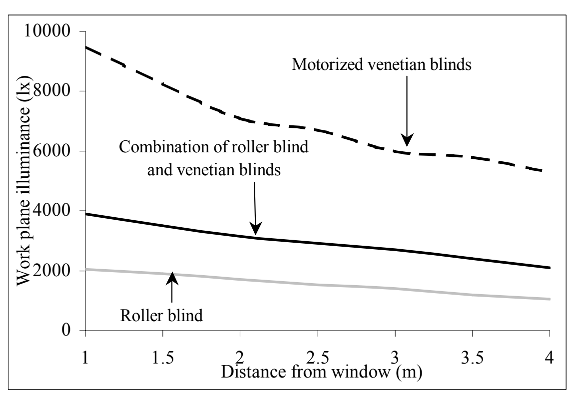

Fig. 5. Illuminance distribution in a typical office on the SW façade (July 15th, 1pm).

SIMULATION RESULTS

Atrium shading

There is an atrium on the southwest façade of the building, extending from the 2nd to the 16th floors. The atrium is not continuous; it is separated every three storeys with a floor slab. The dimensions for each three-storey atrium space are 9m long x 15m deep x 12.75m high. Shading is essential to reduce overheating and peak cooling loads during the cooling season, since the southwest façade receives high amounts of solar radiation (Fig. 2). Thermal simulations showed that temperature in the atrium may reach 45^0C in September (without cooling). The criteria for shading are based on: reduction of heating/cooling loads, maximization of outside view, architectural aesthetics, illumination of adjacent spaces and other operations (air heating, solar chimney). The shading options considered are shown in Figure 6.

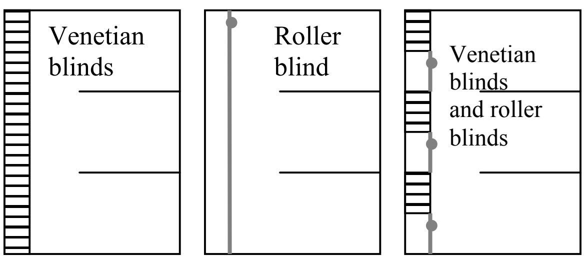

Fig. 6. Shading options for the atrium

Following the same methodology, the illuminance distribution at all heights of each atrium space is calculated hourly for each of the three shading options. Typical results are shown in Fig. 7.

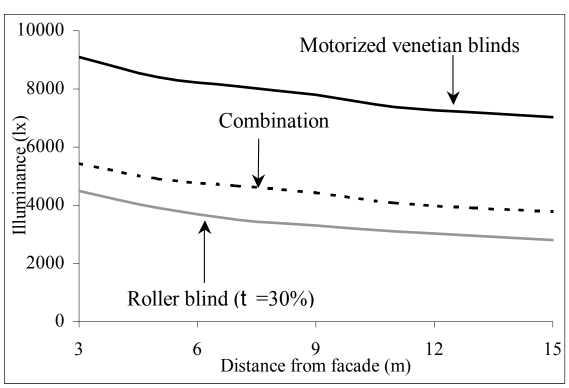

Fig. 7. Illuminance distribution at the ground floor of a three-storey atrium space, July 15th, noon.

Examination of the results of Fig. 5 reveals that the motorized venetian blinds perform better than the roller blind. This is true for all clear days in the year, except for some winter afternoons, when the sun is low and the venetian blinds have to close at a high angle to prevent from glare. The roller blind also performs better during overcast days, since it can be open to allow all the diffuse daylight into the room and maximize view to the outside. Considering the above, and taking into account that many people want to have some control of their luminous environment, the best solution seems to be the combination of a manually controlled roller blind at the bottom part of the window, and motorized venetian blinds operated by the building automation system at the top part of the window, as shown in Figure 1. The venetian blinds block direct sunlight and redirect it towards the ceiling, improving the daylight uniformity in the room. During overcast day, they remain at a position near horizontal to maximize view to the outside and admit much diffuse daylight in the office. The manually controlled roller blind will give the occupants the choice of changing their visual environment and will ensure privacy. Under normal circumstances, the roller blind should be open during overcast days and closed during clear days.

Illumination of adjacent corridors

As shown in Fig. 1, glazings can be placed on the top part of the back wall of a perimeter office, to allow natural daylight to enter the adjacent spaces (corridors). Taking advantage of the daylight reflected towards the ceiling and the back wall by the motorized venetian blinds (Fig. 4), non-perimeter corridors can be illuminated with natural daylight, creating a pleasant visual environment. Special simulations were performed for this case, to calculate the amount of daylight that can be reflected into the corridors and also the illuminance distribution in a 3m wide x 4.25m high corridor at the back of a typical perimeter office of the southwest façade, for every hour in the year, during clear and overcast days. In this case, the methodology used is the following: first, the amount of daylight incident on the back window of the office was calculated (Fig. 9), after computing the view factors between the back window and the eight interior surfaces of the office (including the two parts of the window). The back windows considered in the simulations were 1.3m high x 4m long (same area as the window with the motorized blinds on the opposite wall), and they are assumed single-glazed, to maximize daylight transmission into the corridors.

A part of the corridor (4m long) exactly behind the office was considered and simulated as a seven-surface enclosure (like the case of an office with one window). The reflectances of the corridors surfaces were set equal to 60%, except for the two open sides, where the reflectances were set very close to zero (since there is no wall). The only initial luminous source in this case is the back window. The luminous exitance of each surface and the illuminance distribution in the corridor are then calculated in the same way as for the offices [5]. The motorized venetian blinds perform excellent; in some cases, the amount of daylight is sufficient during clear days even 2.5 behind the office, as shown in Figure 10.

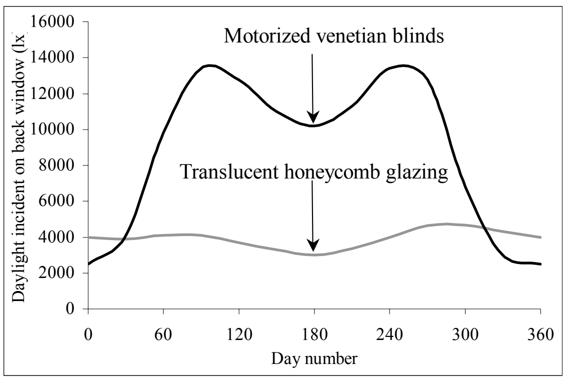

Fig. 9. Illuminance on back window of a perimeter office of the southwest facade (July 15th, noon).

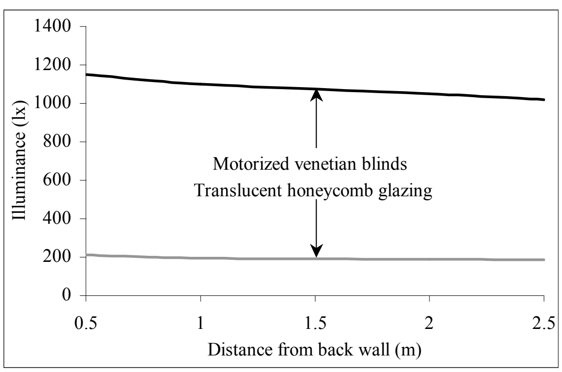

Fig. 10. Illuminance distribution in the corridor (July 15th, noon).

Comparison of lighting control options

Utilization of daylight in perimeter spaces can lead to significant energy savings due to reduction in electricity consumption for lighting if dimmable electric lighting systems are used [1, 5, 7]. In the simulations, the electric lights are dimmed based on a control algorithm developed at the Centre for Building Studies in Concordia University, to always ensure more than 500 lx on the work plane (target illuminance). For a typical 4x4x4.25m high perimeter office, six 32-Watt lamps (T8 type) and two ballasts (20 Watts) are needed, resulting in approximately 13 Watts/m^2 power. Two options were considered for the electric lighting control: (i) continuous dimming of all lamps (0%-100%) and (ii) three-level switching based on on/off operation of three pairs of lamps. The difference between the two control strategies is that, for the three-level switching, the lights are not dimmed, but they are 100% on when there is not sufficient daylight (less than 500 lx) on the work plane, which is assumed to be 0.8m above the floor. The advantages of dimming the lamps continuously are that, first, better visual environment is created (occupants cannot easily realize the changes in the intensity of lights) and second, the energy savings are higher because all the lamps operate at the minimum necessary level, to ensure 500 lx on the work plane. The three-level switching also results in significant energy savings, but the lights turn suddenly on when there is insufficient amount of daylight on the work plane. However, this option is more cost-effective.

The simulations produce the dimming levels (and the operation times) of all lamps for every work-hour in the year, based on the logic algorithm described in Fig. 11, for the configuration of Fig. 1. The motorized blinds operate automatically based on outside illuminance and sky conditions. The roller blind is assumed to be closed during clear days (τ = 20%) and open during overcast days. The algorithm computes the illuminance in pre-selected representative points on the work plane and the electric lights are dimmed (or turn on), starting from deep in the room- where the illuminance level is lower) and proceeding towards the window. If it is necessary (very cloudy days or at night), all six lamps are operating. For all the other cases, only two or four lamps are operating at the optimum level, to ensure at least 500 lx on the work plane surface.

The daily electricity consumption using the two lighting control strategies is also computed for all the days in the year. Clear and overcast days are taken into account in the simulations, based on the clearness index values for each month for the region of Montreal. The results are shown in Fig. 12.

As expected, continuous dimming is more energy-efficient than three-level switching. The two curves are compared with the case when there are no lighting/daylighting controls. These simulations were performed for all facades and perimeter spaces, for every hour in the year, to estimate the total energy savings due to reduction in electricity consumption for lighting in perimeter spaces. Also, the energy savings for spaces adjacent to the atrium were calculated. Moreover, the energy savings due to reduction in electricity use for lighting for the corridor spaces were computed in the same way. The corridor lights are dimmed based on the available daylight transmitted through the back windows. The

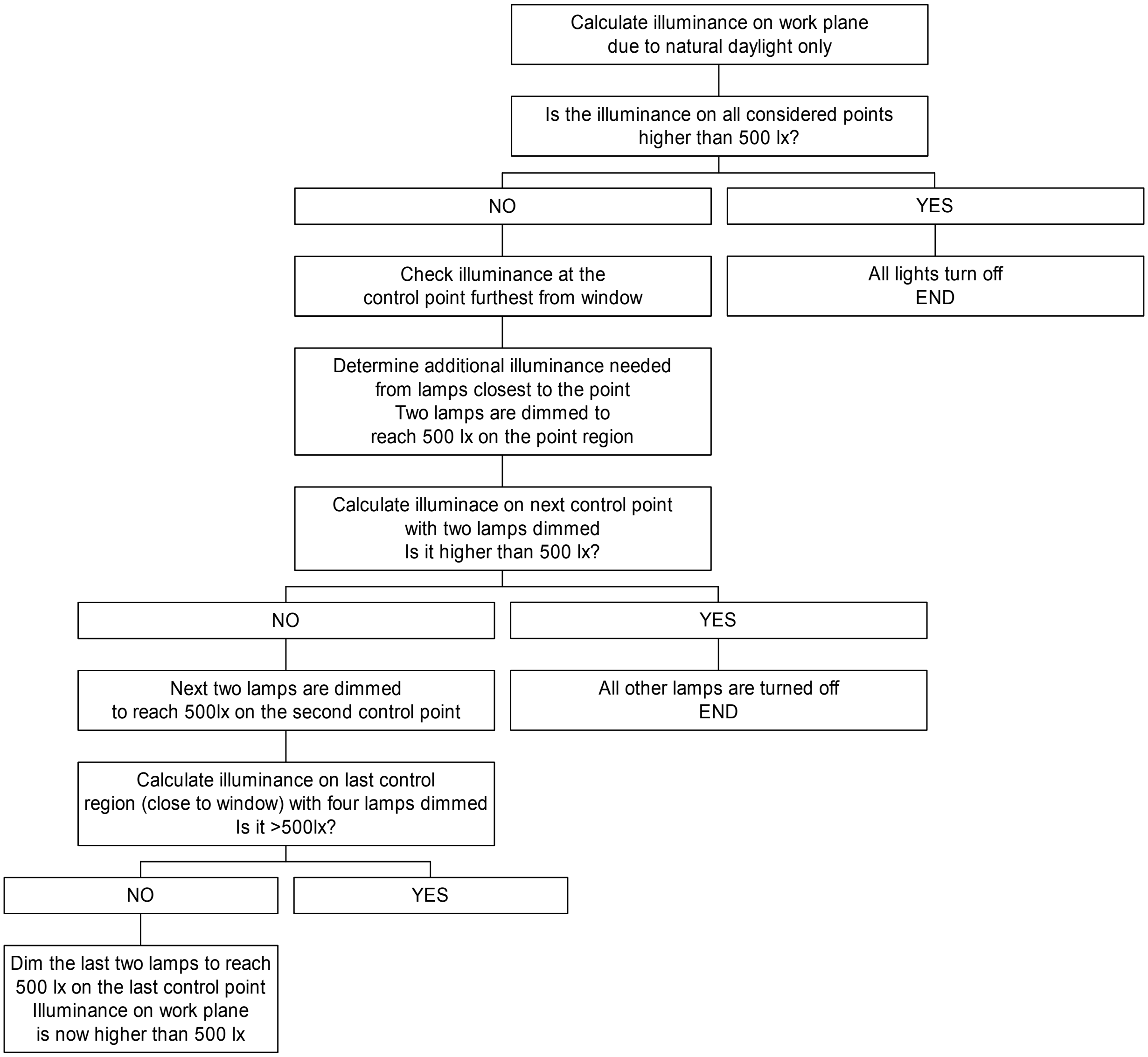

Fig. 11. The control algorithm for dimming

target illuminance is of course lower here (250 lx), based on recommendations of IES [9].

Fig. 13 summarizes the yearly energy savings from each façade in kWh, as well as the resulting energy savings from corridors and adjacent to atrium spaces, using the two lighting control options. The yearly energy savings with continuous dimming reach 334300 kWh (83% compared with the case when no lighting control exists), whereas with three-level switching the energy savings reach 275000 kWh (71%). The difference is not significant -compared to the difference in the cost of the two control systems- and thus the three-level switching was is the more cost-effective option.

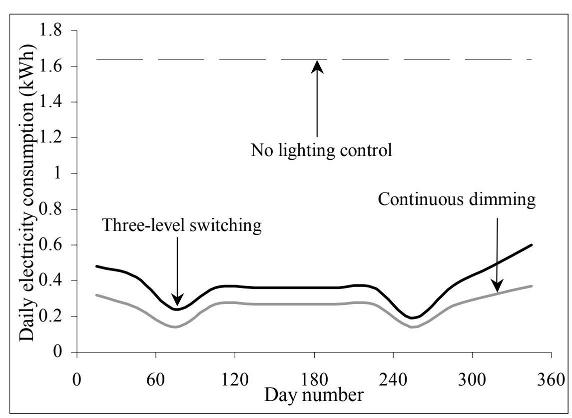

Fig. 12. Mean daily electricity consumption for lighting for the lighting control options (typical perimeter office on the SW façade).

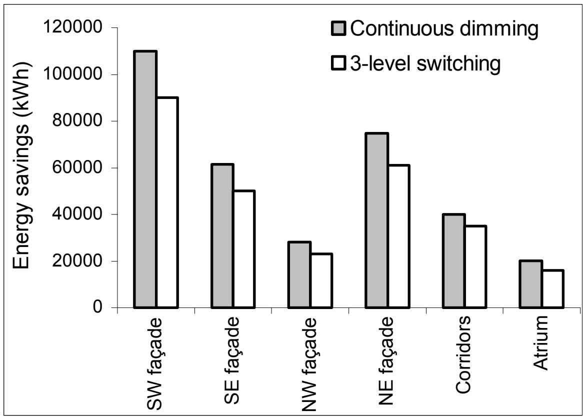

Fig. 13. Energy savings from all spaces with the two lighting control options.

The highest energy savings (90000kWh) are realized from the SW façade, which is the largest and receives high amounts of daylight during the year until late in the afternoon. Nevertheless, the other facades and the non-perimeter spaces also contribute significantly, as shown in Fig. 14. The use of daylight in conjunction with three-level switching of electric lights in non-perimeter spaces (corridors and spaces close to the atrium) may save 51000 kWh per year (approximately 20% of the total energy savings).

The illuminance distribution in perimeter spaces using the optimum shading configuration of Fig. 7 and the three-level switching for lighting control is significantly improved. Daylight uniformity and sufficient amount of light are ensured during the year. A typical result is shown in Fig. 15, for December 15th, 3pm, which is the worst case for the southwest façade. The venetian blinds close at a high angle and the roller blind is also closed, to reduce glare, because the sun is low. The illuminance on the work plane is less than 500lx and four of the lamps are on, resulting in a uniform distribution (around 700 lx) on the work plane. Two roller blind transmittance values are compared. The final uniform light distribution is shown, when the electric lights are operating based on the three-level switching control.

CONCLUSION

Major daylighting and shading options, electric lighting options and associated energy simulations were presented for the new Concordia University Engineering building. Shading is essential since two of the main facades of the building receive high amounts of solar radiation throughout the year. Combined daylighting and shading transient simulations for different shading options were performed. The selection of the optimal shading device type and transmittance is critical; thermal and visual comfort and heating/cooling energy consumption are highly affected by the type and control of the shading device used. Many parameters were taken into account in the decision analysis and illuminance distributions produced by using each shading option were simulated using a radiosity-based analysis.

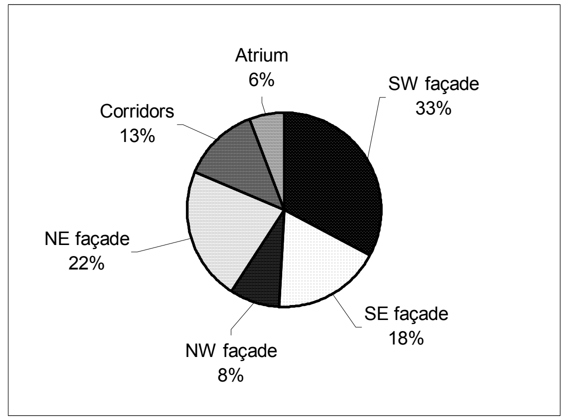

Fig. 14. Distribution of energy savings due to reduction in electricity consumption for lighting in the building.

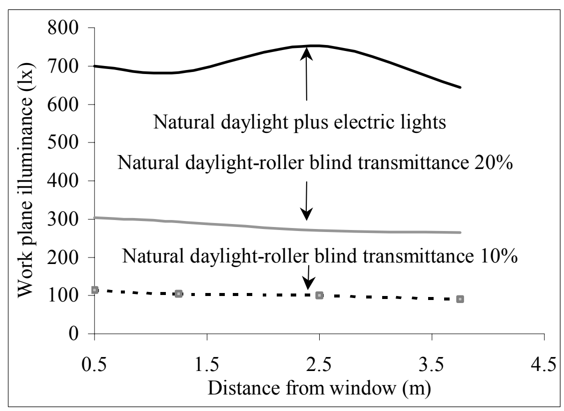

Fig. 15. Illuminance distribution on the work plane for typical office on the SW façade, December 15th, 3pm.

The configuration selected as the optimal solution was a manually controlled roller blind (20% transmittance) at the bottom viewing part of the window and motorized reflective venetian blinds operated by the building automation system at the top part of the window. The venetian blinds block direct sunlight and reflect it towards the deeper parts of the room, creating a pleasant environment and a uniform daylight distribution in perimeter spaces. Moreover, if back windows are used at the top part of the back walls, the reflected daylight may be utilised to illuminate adjacent corridors. The manually controlled roller blind could be kept closed during clear days, to prevent from glare and overheating, and open during overcast days, to allow maximum view to the outside and allow all the available diffuse daylight in the room. Also, it will ensure privacy and will give partial control of the luminous environment to the occupants.

Three ways of shading are considered for the southwest atrium façade. Using the same configuration as for the offices (combination of venetian blinds and roller blinds), natural daylight may reach deep into the building and illuminate the atrium and some adjacent spaces. The roller blind transmittance can be high (30%), to allow more view to the outside.

Two types of electric lighting control were considered, to estimate the energy savings. Although with continuous dimming higher energy savings (83%) and better visual comfort are achieved, the three-level switching is more cost effective and the energy savings are quite high (71%). Calculation of energy savings for all the perimeter spaces and also for other non-perimeter spaces (corridors, spaces adjacent to the atrium) where daylight could be utilized, showed that, using three-level switching, 275000 kWh could be saved yearly due to reduction in electricity consumption for lighting. Furthermore, other energy savings due to reduction in peak cooling loads and energy consumption for cooling and heating -if the selected shading devices are to be used- should be added to the above savings.

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