SIMULATION FOR FAÇADE OPTIONS AND IMPACT ON HVAC SYSTEM DESIGN

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ABSTRACT

This paper presents a simulation study employed for the optimization of the building envelope for a new university building located in Montreal (latitude 45^0N). The study involved simulation of façade design options, taking into account maximization of daylight, reduction in electricity consumption for lighting and optimal control of solar gains. Combinations of motorized shading devices in conjunction with controllable electric lighting systems are investigated in detail. Transient simulations also considered the impact of motorized shading and light dimming on HVAC system sizing and energy consumption for heating/cooling. The resulting energy savings and thermal comfort using an optimum design strategy are discussed.

INTRODUCTION

The area of fenestration in buildings is continuously increasing, driven by two factors- first the higher demand for buildings with much daylight, and second the development of advanced windows with predictable or controlled solar transmittance characteristics (e.g. electrochromic coatings, motorized shading) and high thermal resistance. The increased fenestration areas often result in highly varying heating and cooling loads throughout the year, especially when inadequate amounts of thermal mass are employed. The fragmented nature of the building process, in which no member of the design team considers the overall optimization of the indoor environment, further compounds the problem.

Different types of dynamic building envelope systems have recently been studied and employed in buildings in order to achieve a better performance. The main purpose of these devices is to optimally control solar gains and create a high quality indoor environment. The design of such systems is a complex task; daylighting, shading, peak heating and cooling loads and electric lighting together with their control strategies should all be taken into account when designing a façade. Since the above parameters are interrelated, an integrated approach must be followed in order to attain an optimal solution. The situation is more complex for facades with high solar gains. In this case, shading provision should be considered as an integral part of fenestration system design. One solution is the use of advanced windows with innovative fenestration systems and motorized shading devices (*Rosenfeld et al 2001, Athienitis & Tzempelikos 2002*). They can block direct sunlight and allow diffuse light into the room, thereby eliminating glare and creating a pleasant luminous environment if they operate optimally.

Dynamic control of shading devices, daylighting systems, electric lighting and HVAC system components may lead to minimization of energy consumption for lighting, heating and cooling (*Lee et al, 1998*). At the same time, good thermal and visual comfort can be achieved under continuously varying outside conditions. The objective of this paper is to investigate different façade design options for a new building to reach an optimum solution, based on all factors mentioned above. The effects of each parameter on energy efficiency and human comfort are studied simultaneously. Human control of some of the components is also discussed.

SIMULATION METHODOLOGY

The 17-storey-high building has two main unobstructed facades facing southwest and southeast. The total floor area is about 53000 m^2 while the floor area covered by perimeter spaces is 5000 m^2. The first decision is the fraction of glazing area of the façade. This should be decided in conjunction with the thermal properties of the curtain wall and the type of glazing. The thermal resistance of the curtain wall was set to 3 RSI, to meet energy code recommendations for Montreal. Then a typical floor was selected for energy analysis. For perimeter offices, maximization of daylight utilization is important. Also, these offices usually require perimeter heating. Integrated thermal studies were performed for three glazing R-values (0.52, 0.67, 0.85 RSI) and three fractions of vision area (50%, 65% and 75%). The purpose of this simulation was to determine a combination of glazing thermal resistance and vision (glazing) area fraction so as to minimize the need for perimeter heating and maximize daylight. The mean radiant temperature, operative temperature and radiant temperature asymmetry were calculated 1m from the window for winter conditions. It was found that a glazing with at least 0.67 R-value may eliminate the need for perimeter heating for all cases. This leads to significant capital cost savings and increases the usable area of the perimeter offices. Daylighting calculations (next section) also showed that, by choosing two-thirds of the façade to be clear glass, the amount of daylight is sufficient most of the time. Moreover, the effect of the glazing R-value on the peak loads together with the effect of shading is shown in Fig.8. Thus the combination of 2/3 glass-to-wall area and glazing R-value 0.67 was selected as optimum.

Daylighting and shading analysis

The two facades (SE and SW) receive high amounts of solar radiation during the year and shading provision is necessary to control solar gains, prevent from overheating and eliminate glare. The types of shading devices considered in the simulation are: (i) motorized reflective venetian blinds integrated in the double-glazed window, (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 critical 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.

Detailed hourly simulations were performed in order to calculate the illuminance distribution in typical 4m x 4m x 3.5m perimeter offices for all the above shading options and for both clear and overcast sky. First, the incident daylight (*E*) on each façade was calculated hourly during the year, based on CIE overcast and clear sky models (*CIE, 1989*). The transmitted daylight into the room is calculated next. The amount of transmitted daylight depends on the type of 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 reflect it, 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 day number (*n)* and solar time (*t*) (*Athienitis & Tzempelikos, 2001*). 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. 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%). The transmitted daylight 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 together. Fig. 1 shows the beam effective transmittance for the different shading options during a clear summer day (SW façade). As shown, the motorized venetian blinds allow a lot of daylight during the morning -when the sun is high- but after 2pm they close to prevent direct daylight transmission.

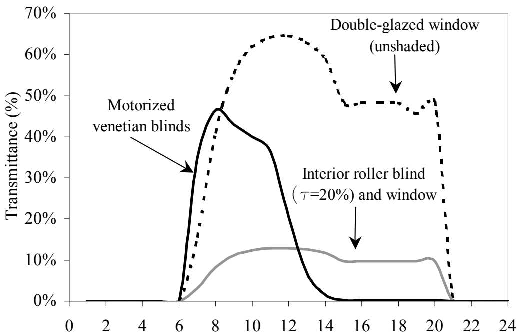

Fig. 1. Transmittance of window/shading device as a function of time (clear summer day).

The illuminance distribution on the work plane after multiple reflections in the room is calculated next, based on a radiosity-based analysis (*Athienitis & Tzempelikos, 2002*). Depending on the type of shading device used, the transmitted daylight calculated in (1) will be the initial interior luminous exitance of the window. If only one shading device is used, the room interior is modeled as a seven-surface enclosure (six walls and one window). 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 (*Athienitis & Tzempelikos, 2002*), after calculating view factors, final luminous exitance of all surfaces (*Murdoch, 1985*), 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 (±10^0 deviation), 25% is reflected downwards (mainly towards floor) and at least 35% is reflected towards the ceiling, as shown in Fig. 2.

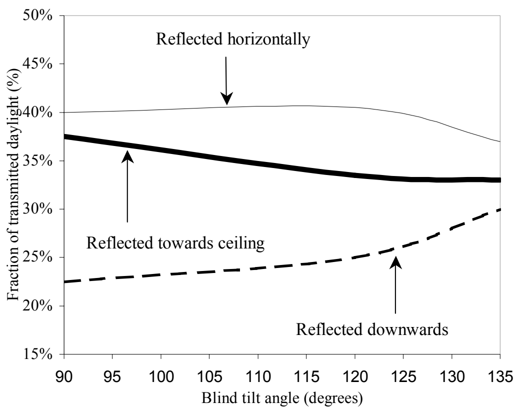

Fig. 2. Directional distribution of transmitted daylight through motorized venetian blinds, for different blind tilt angles (90^0 is horizontal).

This directional distribution of transmitted daylight can change the illuminance distribution on the work plane significantly. Therefore, it was taken into 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 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 daytime hours in the year, considering all the above shading options, for all perimeter spaces, for both clear and overcast days.

Roller blinds may ensure privacy and can be open during overcast days to allow maximum daylight in the room. On clear days, they may diffuse daylight and their transmittance can be low in the bottom half and higher in its upper part. Motorized reflective venetian blinds block direct sunlight, reduce cooling loads (as shown below) and allow some view to the outside. Moreover, they reflect daylight towards the ceiling by adjusting the blind tilt angle in order to block direct sunlight, and improve the daylight uniformity deep in the room. The honeycomb translucent glazing has good thermal resistance, but it may create glare on clear days and can lead to overheating. For most cases, the motorized venetian blinds perform better than the roller blind. Fig. 3 shows the best case; in the summer the sun is high and the venetian blinds allow plenty of diffuse daylight in the room. Fig. 4 shows the worst case; during December and January, the sun is low and the venetian blinds close at a high angle to block direct sunlight. The performance of translucent glazing is not included in the figures, because of very high illuminance values (glare).

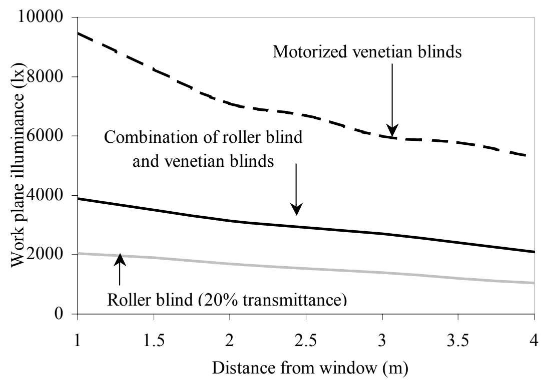

Fig. 3. Illuminance distribution in a typical office on SW façade (clear summer day, noon).

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The thermal transmittance and the control of the shading device are also important when deciding for the best system because they affect significantly the heating and cooling loads as discussed below. The window with integrated venetian blinds has a variable thermal resistance (depending on the blind tilt angle and the outside temperature), which is quite high (around 0.65 RSI).

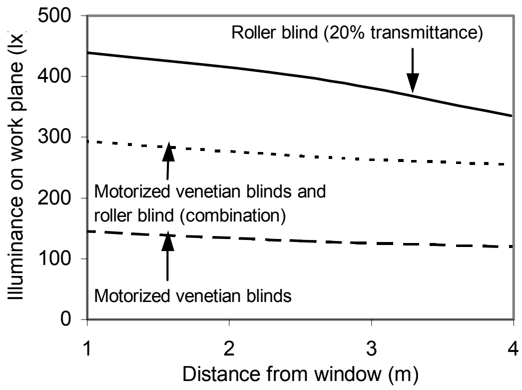

Fig. 4. Illuminance distribution in a typical office on SW façade (clear winter day, afternoon).

Based on the above, and at the same time considering that people would like to have some control on their luminous environment, the optimal solution was found to be that of Fig. 5. This is a combination of motorized venetian blinds (top half of the window) and manually controlled roller blind (bottom half of the window). The roller blind has a smaller resistance but in this case, it is not important since the glazing R-value has been selected as 0.67 RSI. However, their control is very important, and this is shown in Figs 8-10. Nevertheless, in the determination of the best shading/daylighting system the daylighting performance plays a dominant role and overall, the motorized venetian blinds perform better.

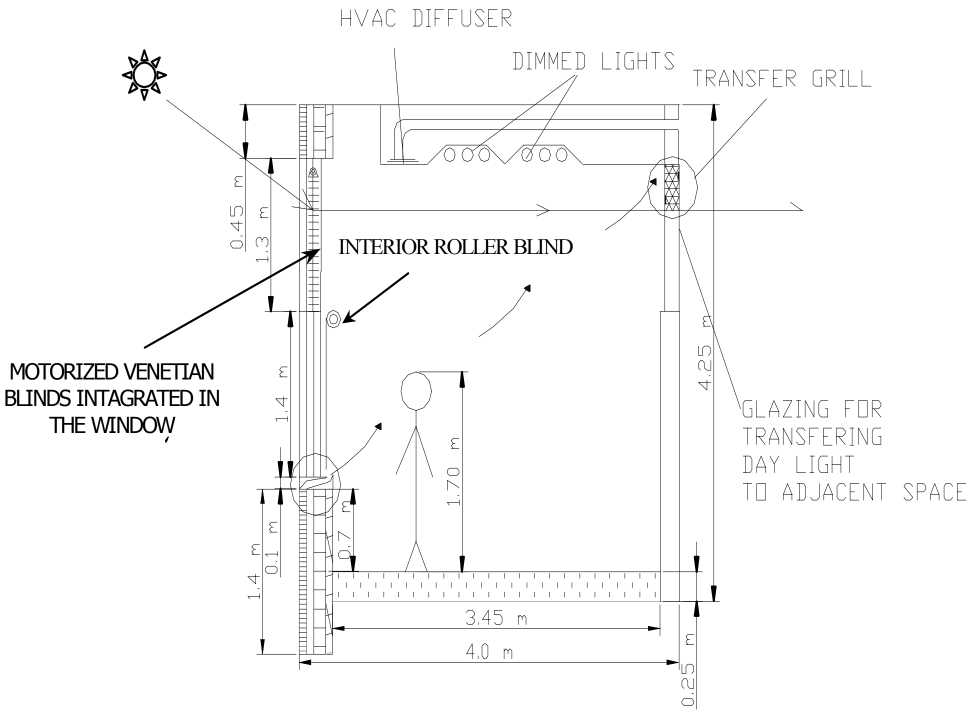

Fig. 5. A multifunctional façade with optimum shading and daylighting options for a typical perimeter office. The top part of the window consists of motorized venetian blinds and the bottom half is a manually controlled interior roller blind.

The venetian blinds block sunlight and improve daylight uniformity in the room, while the manually controlled roller blind gives the occupants the choice of changing -to a certain extend- their visual environment and can provide privacy. Under normal circumstances, the roller blind should be open during overcast days and closed during clear days. Moreover, by using this configuration, the control points are dramatically reduced (1-2 points on each façade).

Electric lighting options and energy savings

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 (*Tzempelikos & Athienitis, 2002, Lee et al, 1998*). 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 perimeter office, three 60W T8 type fluorescent lamps with their 10W ballasts were assumed (12W/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 one, two and three 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 first, a better visual environment (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, for the configuration of Fig. 5. The motorized blinds operate automatically based on outside illuminance and sky conditions. The roller blind is assumed to be closed during clear days 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/ turn on, starting from deep in the room-lower illuminance- and proceeding towards the window. If it is necessary (very cloudy days or at night), all three lamps are operating. For all the other cases, only one or two lamps are operating at the optimum level, to ensure at least 500 lx on the work plane. The daily electricity consumption using the two lighting control strategies is also found for all days in the year. Clear and overcast average 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. 6.

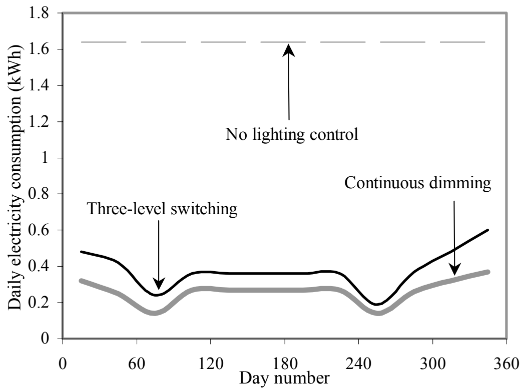

Fig. 6. Comparison of mean daily electricity consumption for lighting using continuous dimming, three-level switching and no lighting control in a typical office on SW façade.

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. The annual energy savings using continuous dimming reach 334300 kWh or 67 kWh/m^2 (83%), whereas using three-level switching they reach 275000 kWh or 55 kWh/m^2 (71%). The 8% difference (59300 kWh) is noticeable, but when compared with the difference in the cost of the two systems it seems that the three-level switching is the most cost-effective option. The illuminance distribution in perimeter spaces using the optimum shading configuration of Fig. 5 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. 7, 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 two of the lamps are on, resulting in a relatively uniform distribution (around 700 lx) on the work plane. For most clear days in the year, only one lamp is operating for a few hours and the work plane illuminance varies between 500lx and 600lx. In Fig. 7, two roller blind transmittance values are also compared. From simulations throughout the year, it seems that 20% transmittance is better than 10%. More than 20% transmittance may lead to overheating in the summer and increase of cooling loads. The final uniform light distribution is shown, when the electric lights are operating based on the three-level switching control.

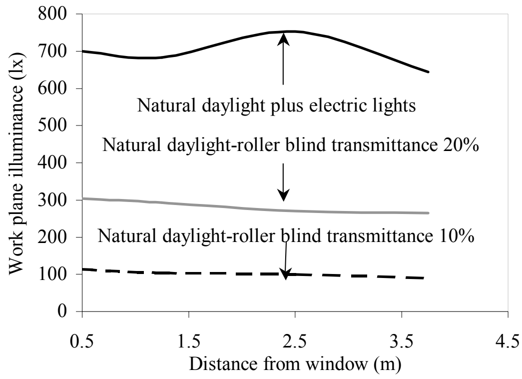

Fig. 7. Illuminance distribution on the work plane in a typical office on SW façade (December 15th, afternoon).

Reduction in heating and cooling loads and energy consumption

Detailed transient thermal studies were performed to investigate possible reduction in peak cooling/heating loads and reduction in energy consumption for heating and cooling. The simulations were done for heating design days (cold cloudy and sunny) and for cooling design days (hot sunny) using software based on a Mathcad electronic book (*Athienitis, 1999*). Solar gains, conduction gains, lighting and other internal gains are all taken into account and the results are based on detailed transient analysis (*Athienitis & Santamouris, 2002*). The most important thing in this analysis is to consider building envelope parameters together with the shading devices and their control, as well as light dimming, in order to find their effect on the loads and energy consumption.

Simulation results show that the motorized shading devices reduce dramatically the peak cooling loads and energy consumption. Cooling loads are further reduced because the lights are dimmed. Figure 8 shows the impact of different options on peak heating and cooling loads. The heating analysis is for a cold January day, while the cooling analysis is for a hot sunny summer day. This figure presents all the major findings of this part of the simulation. The peak heating load is of course highly dependent on the glazing R-value. A glazing with R-value=0.52 is not suggested also for this reason. The maximum reduction in peak cooling load is due to motorized control of shading devices (last group of bars), but there is also a significant reduction due to light dimming using three-level switching (second group of bars). Also, there is no noticeable reduction in the peak cooling load due to increasing window (or wall) R-value because most of the cooling load is due to solar gains, lighting and other internal gains. The reduction in cooling capacity due to motorization of shading devices and light dimming reaches 513 kW for both cases (R=0.67 RSI and R=0.85 RSI). In terms of cooling performance, they are both equal. These results together with the elimination of perimeter heating and the big difference in the cost of the glazing, justifies the choice of R=0.67 versus R=0.85 for the glazing. Fig. 9 shows the effect of light dimming and shading device motorization on daily cooling load (for all perimeter spaces).

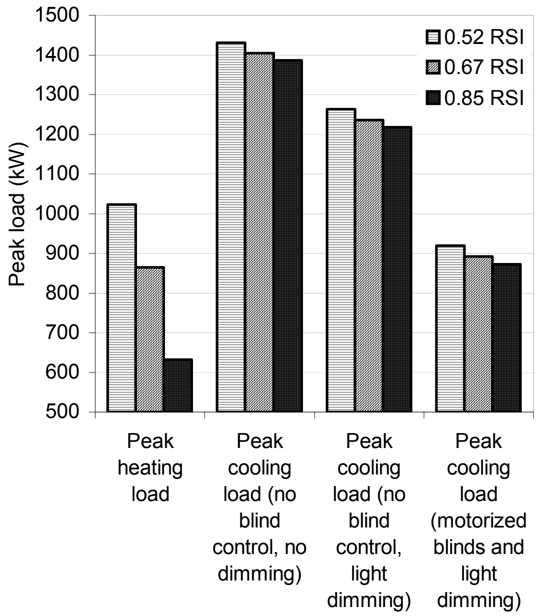

Fig. 8. Peak heating and cooling loads for different glazing R-values and the effect of blinds control and light dimming (perimeter floor area is 5000 m^2).

The above parameters have similar effects on the energy consumption for heating and cooling (except for the loads). Fig. 10 summarizes the annual energy consumption for heating and cooling for the parameters of Fig. 8. These results correspond only to perimeter spaces (interior zones are not considered here). The reduction in cooling electricity consumption is 740 MWh (148 kWh/m^2) due to light dimming and 1540 MWh (308kWh/m^2) due to blinds control. As shown in Fig. 10, the operation of motorized shading devices in conjunction with three-level switching of the lights reduces dramatically the energy consumption for cooling. The total energy savings calculated above pay for the cost of motorized shading devices and glazings in less than three years.

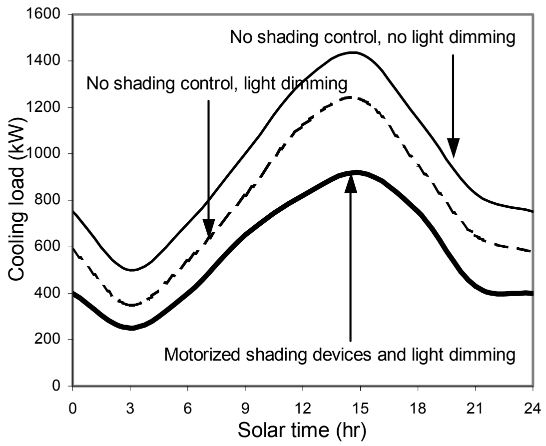

Fig. 9. Impact of light dimming and motorized shading on cooling load during a hot summer day.

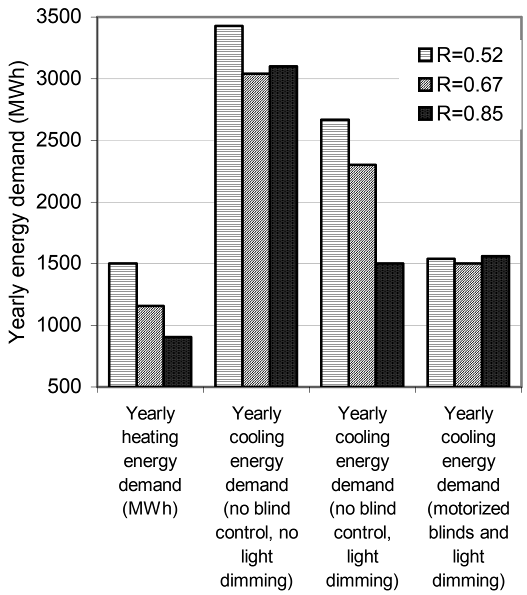

Fig. 10. Impact of glazing thermal resistance, blind control and light dimming on annual heating and cooling energy consumption (perimeter floor area is 5000 m^2).

CONCLUSIONS

The major objectives of this simulation design study were to maximize daylight utilization, control solar gains optimally, reduce energy consumption for heating, cooling and lighting and peak loads, while maintaining good thermal and visual comfort. By choosing two thirds of the façade area to be glass with R-value of approximately 0.67 RSI for the particular building considered, perimeter heating could be eliminated. Maximization of daylight is achieved by selecting clear glass for the facades. The selection of shading devices and their control is critical. Thermal and visual comfort are strongly affected by the type and control of the shading device used. The daylighting performance of three shading devices and their combinations was estimated by detailed hourly daylighting simulations. The combination of motorized venetian blinds integrated in the windows and operated by the building automation system with manually controlled interior roller blinds in the lower portion of the window was found to be an optimal solution. The occupants have some control on the luminous environment, without affecting the performance of the motorized venetian blinds.

Two lighting control strategies were compared and the three-level switching seems the most cost-effective option. The operation of the motorized blinds in conjunction with the controllable electric lighting system ensures adequate illuminance all the time and uniformity on the work plane (500lx). Peak cooling loads and cooling energy consumption are dramatically reduced -by 40%- if the proposed strategy is used (not considering ventilation loads). When calculating heating and cooling energy consumption and peak loads, it is very important that the shading devices and their control are taken into account, since the impact of these factors in the results is strong. Further research is underway in order to develop a general methodology that allows integrated design of shading devices/fenestration systems, electric lighting systems considering their impact on heating, cooling and lighting energy consumption.

NOMENCLATURE

E	illuminance [lx]
n	day number
τ	transmittance
G	transmitted daylight [lx]
t	solar time [hr]

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