The effect of shading design and control on building cooling demand

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ABSTRACT

Shading provision should be considered as an integral part of fenestration system design for commercial and office buildings, in order to balance daylighting requirements versus the need to reduce solar gains. Utilization of daylight in buildings may result in reduction in electricity consumption for lighting but also in high cooling demand if excessive solar gains are admitted in the working space. Moreover, visual comfort should be ensured especially for perimeter office spaces. Shading devices can control solar gains and simultaneously allow adequate daylight to the interior. In this paper, the simultaneous effects of shading device properties and control on building cooling demand are evaluated using a coupled lighting and thermal simulation module. The interactions between cooling and lighting energy use in perimeter spaces are analyzed as a function of window-to-wall ratio and shading parameters. Roller shades are used as an example. Shading device type, properties and control have a significant impact on building cooling demand. An integrated approach for dynamic operation of fenestration systems in conjunction with controllable electric lighting systems could lead to minimization of energy consumption for cooling in perimeter spaces, depending on climatic conditions and orientation.

1. INTRODUCTION

Building design is a complicated process during which critical decisions concerning the different systems related to the building are made at the early stage. For perimeter spaces, an integrated thermal and daylighting analysis is required, since the two domains are inter-related.

Utilization of daylight in buildings may result in significant savings in electricity consumption for lighting (Lee et al., 1998), while the benefits in terms of higher productivity of office workers are also high (Heschong, 2002). Nevertheless, large fenestration areas often result in excessive solar gains and highly varying heating and cooling load.

Advanced glazings and innovative daylighting/shading systems are being studied in order to control solar gains and create a high quality indoor environment. A major factor in the evaluation of the performance of such devices is the detailed optical and thermal characterization. These properties are usually not provided by manufacturers and there is no standard procedure for measuring them. They can be estimated using experimental techniques (Rosenfeld et al., 2001, Andersen et al., 2005), using complicated theoretical models (Pfrommer et al., 1996) or using advanced software (Reinhart and Walkenhorst, 2001).

This paper presents an integrated approach for fenestration and shading design analysis and optimization at the early stage. First, window-to-wall ratio for is determined based on integrated performance indices obtained by the continuous interaction between transient hourly thermal and lighting simulation. Daylight availability ratio and reduction in peak thermal loads and energy consumption are identified as initial criteria. The impact of different shading properties on visual comfort and overall energy performance of perimeter spaces of office buildings is shown by means of simulation and the significance of control strategies is discussed.

2. SELECTION OF WINDOW SIZE

A parametric sensitivity analysis was performed to investigate the effect of window size and orientation on combined daylighting and thermal performance of office buildings. A typical perimeter office space in Montreal was used as a base case. The effect of window size on electric lighting demand is also presented. If electric lights are dimmable, energy consumption is further reduced and the effect on cooling load is discussed. Results allow the selection of window size for each orientation, based on priority criteria. Window size is expressed as window-to-wall ratio for generalization of results. Initially, two factors are considered for selection of window-to-wall ratio of the façade: (i) the ability to provide adequate daylight into the space and (ii) the impact on peak heating and cooling load and energy consumption. Although there are many other parameters which should be taken into account when selecting window size, such as glare, thermal comfort, or even aesthetics, those should be evaluated at a second step, when shading devices are also considered in the integrated design process.

2.1. Daylight availability

A yearly daylighting analysis was performed in order to study the daylight availability in the space. Values of direct normal irradiance and diffuse horizontal irradiance were obtained using a TMY data file for Montreal and then process by a solar radiation engine in TRNSYS in order to get corrected horizontal irradiance hourly values for one year. Then the Perez irradiance model (Perez et al., 1990) was used to predict beam and diffuse solar radiation on tilted surfaces, for the four major orientations. The Perez luminous efficacy models were then employed to predict beam and diffuse illuminance values incident on the façade, improving the results of a previous study (Tzempelikos and Athienitis, 2005). Assuming a double-glazed window, based on MNECCB recommendations for Montreal), the transmitted daylight was calculated for each hour in a year. Hourly transmittance values can be obtained as a function of solar incidence angle, which could eventually be expressed only as a function of day number and solar time, for convenience in hourly simulation. Then the hourly daylight distribution on the work plane was calculated using a radiosity-based method (Athienitis and Tzempelikos, 2002).

Daylight Availability Ratio (DAR) is computed next as a function of orientation and Window-to-Wall Ratio (WWR). DAR is defined as the fraction of working time in a year during which sufficient daylight (more than a pre-specified set point, 500 lx) is available on the work plane. This single number contains all the information about sky conditions, window properties and orientation and can be used as a generalized index to describe the daylighting efficiency of a space. Figure 1 shows the DAR results for Montreal. This figure shows an important result: there is a critical WWR, above which further increase in window size does not contribute to DAR. For example, for south-facing facades, the critical WWR is about 30%.

2.2. Electric lighting consumption

The study included the effect of WWR on electricity consumption for lighting since electric lighting usually accounts for a large part of energy consumption in office buildings. The simultaneous impact of lighting control is also investigated. Electric lights were assumed to turn off when there is enough daylight (500 lx) and to switch on (no dimming) when less than 500 lux are available on the work plane. The annual average electricity consumption for lighting can then be calculated directly using the results of the daylighting simulation. Generally, this depends on the efficiency of the lighting system and the type of lighting used. For each window-to-wall ratio, the average annual electricity consumption for lighting is:

$$E_L = P_L \cdot A \cdot t_y \cdot (1-DAR) \qquad (1)$$

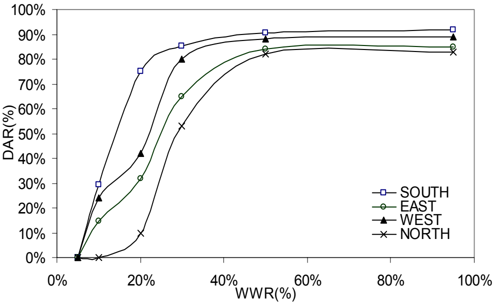

Figure 1: DAR as a function of WWR.

where:

P_L: is the installed lighting power (W/m^2),
A: is the total floor area (m^2),
t_y: is the number of working hours in a year.

The annual average electricity consumption for lighting as a function of window-to-wall ratio for different orientations is shown in Figure 2. Following the daylighting analysis, curves reach a point beyond which further increase in WWR results in no extra savings.

A direct correlation between electric lighting consumption and DAR is established (Figure 3). Reduced electric lighting operation due to daylight usage also results in reduction in internal gains and thus reduction in cooling load and cooling energy consumption during the summer. Cooling energy consumption is reduced at least by 20% if daylighting is taken into account, assuming on/off operation of electric lights (Figure 4). If continuous dimming was assumed in conjunction with occupancy sensors, energy savings are even higher. Selection of WWR is made based on daylighting and thermal considerations (Tzempelikos and Athienitis, 2005). For the south-facing case, 30% WWR is selected.

3. THE IMPACT OF SHADING

Maximization of daylight usage is desired because visual quality is ensured, occupants’ productivity is increased and electricity consumption for lighting is reduced. Nevertheless, daylight is only the visible portion of solar radiation. Unshaded fenestration products become sources of radiant heat by transmitting solar radiation and by emitting long-wave radiation to dissipate some of the absorbed solar energy. Moreover, problems associated with glare and visual discomfort are inevitable if direct solar radiation is transmitted inside the space. Shading provision is therefore necessary in order to prevent thermal and visual discomfort.

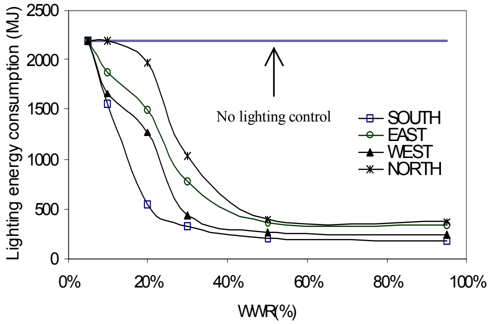

Figure 2: Annual electricity consumption for lighting (on/off control).

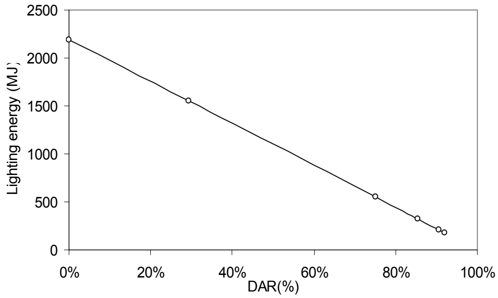

Figure 3: Correlation between electric lighting energy consumption and daylight availability.

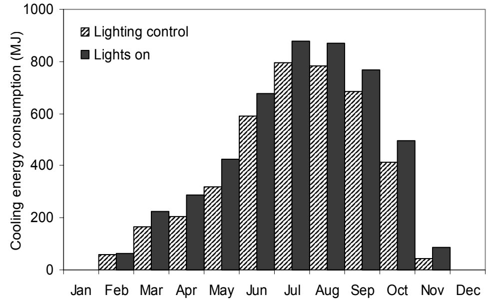

Figure 4: The impact of lighting control on cooling energy consumption.

Shading devices are essentially a second link between daylighting and thermal performance of perimeter spaces. Thus, an integrated analysis should be carried out in order to take into account interactions between different parameters and to attain optimal results. However, with few exceptions (Clarke et al., 1998, Lee et al. 1998, Citherlet and Scartezzini, 2000, Johnson et al., 1984, Tzempelikos and Athienitis, 2003, 2005), an integrated façade analysis is not applied at the early design stage, when critical decisions with small economic impact could lead to significant energy savings during the lifetime of the building and simultaneous improvement in interior conditions. Advanced energy software and simulation tools can handle these problems, but there are still limitations in the process such as importing properties from existing databases and requirements for detailed input data, which are not available at the initial design stage. There is no systematic methodology for selecting optimal properties of shading devices, based on early integrated design of facades. The most effective means of establishing fenestration annual energy performance is through detailed, dynamic, hourly computer simulations for the specific building and climate of interest.

3.1 Shading parameters affecting the energy performance of a space

The effect of shading on visual and thermal comfort and energy performance is determined by three main parameters: (i) the type of shading device (ii) the thermal and optical properties of the shading device and (iii) the considered control of the shading device (if any). Dynamic control of motorized shading devices, fenestration devices, electric lighting systems 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. For office spaces, it is suggested that direct sunlight is not allowed to enter the room, in order to prevent from overheating and glare problems. Climatic conditions and daylight availability play a major role in the design and control of a shading system. For example, for a hot climate, priority could be given in cooling load reduction. Furthermore, in order to be consistent with the integrated design process, the type of control strategy used has to be decided simultaneously with the type of shading device used and with the selection of its optical and thermal properties. This iterative process shall lead to overall optimization of shading systems design and operation, with respect to combined energy efficiency and human comfort.

3.2 Selection of shading device properties and control based on integrated thermal and daylighting simulation – Roller shades

This section presents an application of the integrated methodology for the case of exterior roller shades on a south-facing façade with 30% WWR. Starting from the daylighting analysis, DAR is computed as a function of roller shade visible transmittance (which is assumed constant). Although this assumption could be valid for low transmittance values, it contains errors for higher values and different shade materials. Software like WIS (van Dijk, 2002) or bi-directional transmittance measurements (Andersen et al., 2005) can be used however as input in the transmission model to account for different transmission functions. The effect of different control options showed that simple control of the shade (closed when direct light is present) could result in 30% increase in DAR (Tzempelikos and Athienitis, 2005). Manual control of shades results in probability operation functions used in Daysim or Lightswitch (Reinhart, 2005). The simultaneous impact of shade transmittance on annual lighting energy consumption (calculated using the daylighting results) is presented in Figure 5.

A transient detailed finite difference thermal module runs simultaneously with the daylighting engine. Non-linear heat transfer convective coefficients, schedules and thermal mass effects are incuded in the model. The internal gains due to lighting are read from the dayligthing module, which runs continuously as a function of shade transmittance. The thermal simulation timestep is 5 minutes, to ensure accuracy and stability of results.

The roller shade is controlled based on daylighting considerations and at the same time the cooling energy consumption is calculated as a function of transmittance, taking into account shade operation and control in electric lighting. Figure 6 shows the integrated analysis results. The curve showing the sum of annual cooling and lighting energy consumption is a key indicator for identifying the optimum transmittance of the shading device. Optimum energy performance is achieved when daylighting benefits due to reduced electric

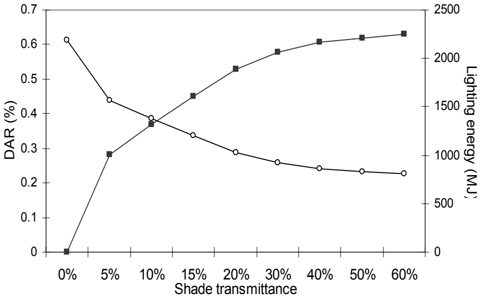

Figure 5: Impact of shade transmittance on DAR and lighting energy consumption.

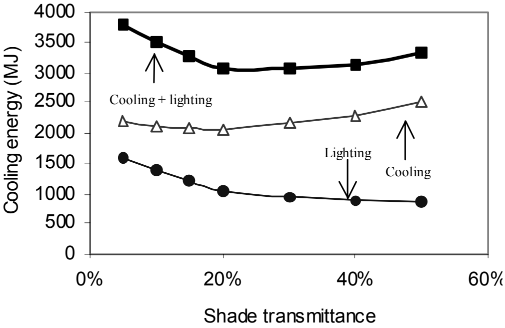

Figure 6: Cooling energy demand as a function of shade transmittance.

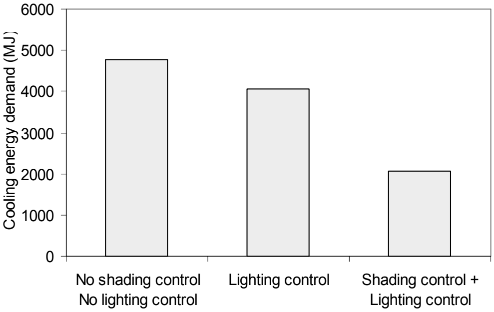

Figure 7: The impact of shading and lighting control on space annual cooling energy demand.

due to reduced electric lighting usage and also due to reduction in cooling energy exceed the increase in energy consumption due to increased solar gains. The curve reaches a minimum at $\tau \approx 20\%$. Considering the results of Figure 5, selection of optimum shading device transmittance should be made with respect to daylight also. For transmittance values higher than 20-30%, daylight utilization is no further increased. Therefore the optimum roller shade transmittance is selected close to 20% for this case.

Although 20% transmittance value satisfies daylighting and cooling requirements, it is expected that a roller shade with 20% transmittance would create glare problems. A solution to this inconvenience is the separation of window area in two parts. The bottom part should have a lower transmittance than the upper part, but the average should approach 20%. For example, this could be achieved using venetian blinds in the upper part, or a roller shade with variable transmitance.

The impact of lighting control and shading control (for optimum transmittance value) is shown in Figure 7. A balance between daylighting, electric lighting and cooling leads to reduction in 50% in cooling energy, comparing with the base case. This should be taken into account when sizing the HVAC system at the early stage. At the same time, glare could be eliminated, as described above.

4. CONCLUSION

A simulation-based integrated thermal and daylighting analysis for building facades was presented. The objective was to optimize fenestration performance for perimeter office spaces, with respect to energy efficiency and human comfort. Daylighting and thermal effects were taken into account, but the dominant initial criterion was initially maximization of daylight utilization. The daylighting performance of a window was expressed by annual daylight availability ratio, a generalized parameter that includes the effects of climate, orientation and window optical properties. Correlations between performance indices generated by the continuous interaction between lighting and thermal simulation provide a way for selecting window-to-wall ratio of a facade.

The need for shading and the complexity of linking daylighting and thermal aspects when designing and controlling a shading device were discussed. The interactions between daylighting and thermal parameters and the effects of daylight utilization in overall energy performance were studied. The type of control should be decided simultaneously with the selection of shading device type and properties using an integrated thermal and daylighting approach. Climatic conditions play a major role in fenestration system design and control.

An exterior roller shade was used as an example of integrated analysis. It was shown that for 20% transmittance, simultaneous control of a shading device on a south-facing façade (in Montreal) and a lighting system could lead to minimization of energy consumption for lighting and cooling, and maximization of daylight utilization. The properties of shading systems (if not the type) should vary by orientation; the performance indices are very sensitive to orientation and climate. Finally, this type of detailed integrated analysis should be performed during the early design stage, when critical decisions will have a major impact on energy performance during the lifetime of the building.

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