DEVELOPMENT OF A METHODOLOGY FOR FENESTRATION DESIGN OPTIMIZATION

Athanassios Tzempelikos   Andreas K. Athienitis

Department of Building, Civil & Environmental Engineering

Concordia University

1257 Guy Str., H3H 1H5, Montreal, Quebec, Canada Tel.: +514-848-8791, Fax: +514-848-7965

agtzemb@alcor.concordia.ca   athiena@alcor.concordia.ca

ABSTRACT

This work is part of a research project on optimization of facades of commerial buildings at the early design stage. Shading devices are utilized to control solar gains and simultaneously provide adequate daylight to the interior. Simulation is employed to quantify the major impact of fenestration and shading systems on visual and thermal comfort in perimeter spaces, but also on energy consumption, peak loads and possibly HVAC system sizing. Moreover, automated operation of shading devices in conjunction with dimmable electric lighting systems and HVAC system components could lead to minimization of energy consumption for lighting, heating and cooling. An integrated approach should be followed when designing and controlling fenestration and shading systems, in order to obtain optimal solutions.

INTRODUCTION

Building design is a complex process in which critical decisions concerning the different systems related to the building are made at the early stage. The daylighting and thermal performance of perimeter spaces depends on fenestration design. Fenestration area in commercial buildings is continuously increasing, driven by the higher demand for buildings with much daylight. It is well known that utilization of daylight in buildings may result in significant savings in electricity consumption for lighting [15], while the benefits in terms of higher productivity of office workers are also high [10]. Nevertheless, large fenestration areas often result in excessive solar gains and highly varying heating and cooling loads throughout the year, especially when inadequate amounts of thermal mass are present. In addition, intense daylight leads to glare problems.

Innovative daylighting/shading systems and dynamic building envelope elements such as prismatic panes and light-redirecting systems [5,16], but also advanced glazing products like electrochromic, are being invented and employed during the last decade in order to control solar gains and create a high quality indoor environment. A major factor in the evaluation of the performance of advanced fenestration/shading systems is the determination of their optical and thermal properties. These are usually not provided by manufacturers and there is no standard procedure for measuring them. They can be estimated using various experimental techniques [1,9,21] or using complicated theoretical models and with the aid of advanced software [17-20].

Shading provision should be considered as an integral part of fenestration system design, especially for south-facing facades of buildings. Shading devices are multi-purpose: they can block direct sun and solar gains during the cooling season, allow the maximum amount of daylight (and solar heat) during the heating season, control the sunlight by diffusing it into the space without causing glare on clear days, while, at the same time, transmit all the available daylight on overcast days [24]. 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 [14,23].

This paper presents an integrated approach for fenestration and shading design analysis and optimization at the early stage. First, optimum window size -defined as window-to-wall ratio for generalization- is determined based on transient hourly thermal and daylighting simulation for one year. Daylight availability ratio and reduction in peak heating and cooling loads are identified as initial criteria. Using an exterior roller shade as an example, the impact of shading properties on visual and thermal comfort and overall energy performance of a perimeter ofice is shown; the significane of control strategies is discussed and guidelines for finding optimal properties are presented.

FENESTRATION AND SHADING: THE KEY

Fenestration systems are the link between daylighting and thermal performance of perimeter spaces. They are the most important envelope element in office buildings. They can provide interior spaces with daylight, view and solar heat while at the same time they could be the cause of thermal and visual discomfort, excessive heat gains/losses and high heating/cooling load. The balance of positive and negative influence of solar radiation on building energy use and human comfort is complicated. Solar radiation accompanies the admission of daylight, which contributes to visual comfort and reduction in electric lighting energy consumption. High solar gains result in increase of cooling load. Also, appropriate control of electric lights can reduce peak cooling load. Problems associated with glare and visual discomfort are inevitable if direct solar radiation enters the room. In addition, thermal problems arise if no shading is used.

Shading devices are a viable solution. The selection of the type and properties of these devices is critical; it will determine daylighting performance, energy consumption for heating, cooling and electric lighting and peak loads. It has a significant impact on visual and thermal comfort. As a result, the design of advanced fenestration/shading systems is a complicated task. The optical and thermal characteristics of these devices should be first evaluated in order to estimate their effect on interior conditions [2,22]. Impact on work plane illuminance levels, peak heating and cooling loads and electricity consumption for lighting 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 significance of integration in building design is well explained in [8]. Performances on advanced glazing systems based on integrated simulation in the frame of IMAGE projetc are described in [7]. An optimum cooling and lighting energy balance between the window and the lighting system may be identified and utilized [14]. Integrated daylighting and thermal analysis shall lead to selection of optimum system properties and dynamic control (if any), with objective to reduce energy consumption for lighting, heating and cooling while at the same time maintain good thermal and visual comfort [11, 23]. This may result in the design of multifunctional facades [24,26].

Glass ratio varies from building to building. Before analyzing the effects of shading, a technique to select the window relative size is presented in the next section.

OPTIMUM WINDOW SIZE

A parametric sensitivity analysis for investigating the effect of window size and orientation on combined daylighting and thermal performance of office buildings is performed. A single perimeter office space in Montreal with one window is used as a base case, to systematically study the effect of window size on daylighting, peak heating/cooling loads and overall energy consumption. The effect of window size on electric lighting demand is also presented. Window size is expressed as glass-to-wall ratio for generalization of results. Initially, two factors are considered for the optimization of the glass ratio of the façade: (i) the ability to provide adequate daylight into the room and (ii) the reduction in 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 will be evaluated in a second step, when shading devices are also considered in the integrated design process.

Daylighting considerations

We refer to daylight as the visible portion of solar radiation, to separate the luminous from the thermal effects of solar energy. A base-case scenario is created; a 4m x 4m x 3m high perimeter office space in Montreal is considered, with one window. For the base case only glass-to-wall ratio and orientation will vary in order to isolate the effect of these parameters for a typical office space. A typical double-glazed window (clear glass) is assumed for the base case. The window-to-wall-ratio is used as a continuous function (0% to 100%) for all orientations. Daylight Availability Ratio (DAR) is used to quantify the daylighting "efficiency" of the window. DAR is defined as the fraction of time in a year during which sufficient daylight (more than a pre-specified set point) is available on the workplane - assumed to be 0.8 m from the floor. The calculation of DAR is done as follows. First, the available amount of incident daylight on the façade is computed by hourly simulation [6,25]. A separate analysis is performed for clear and overcast days. This could be achieved using correlations of average diffuse fraction of radiation with average clearness index [13], or using average cloud cover data. The transmitted daylight in the room is computed using effective beam and diffuse effective transmittances of the window. Hourly transmittance values are calculated for each surface. The total amount of transmitted daylight is calculated by:

$$G(n,t)=E_d(n,t)\cdot\tau_d(n,t)+E_b(n,t)\cdot\tau_b(n,t) \qquad (1)$$

where

G is the total amount of transmitted daylight (lx)
E_d is the diffuse daylight incident on window (lx)
τ_d is the window diffuse transmittance
E_b is the direct daylight incident on window (lx)
τ_b is the window beam (direct) transmittance
n is the day number in the year, n=0..365
t is an hour index, t=1..24

The daylight distribution on the workplane (assumed at 0.8 m height) is calculated next. Under overcast sky, the diffuse light entering the space is assumed to be distributed uniformly on all room surfaces, and a radiosity-based method is applied to find work plane illuminance [25]. For clear sky, a division must be made between direct and diffuse parts of transmitted light. Daylight Availability Ratio is calculated next. A target workplane illuminance is selected (500 lux) and hourly values of work plane illuminance are computed for each month during working hours (9am –5pm) separately for clear and overcast days. The simulation model produces 70080 hourly values of work plane illuminance during the year, for the four major orientations and two sky conditions. The ratio (%) of the hourly illuminance values that is higher than 500 lux contributes to DAR. For each month, DAR for clear days and for overcast days is then averaged based on the average number of clear and overcast days in each month calculated previously. The number of days are used as weights; for example, if (a_1) clear days and (a_2) overcast days happen in a particular month, and (DAR_1) and (DAR_2) are the respective availability ratios calculated from the hourly daylighting simulation, the averaged DAR for that month would be (for a specific orientation):

$$\overline{DAR}_{month} = \frac{a_1 \cdot DAR_1 + a_2 \cdot DAR_2}{a_1 + a_2} \qquad (2)$$

Then the average yearly DAR is calculated from:

$$\overline{DAR}_{annual} = \frac{\sum_{January}^{December} \overline{DAR}_{month}}{12} \qquad (3)$$

Fig. 1 summarizes the daylighting simulation results. For south windows, DAR reaches 63% for 20% glass ratio. In other words, natural daylight provides the space with at least 500 lux for more than 63% of working time if only 20% of the south façade is glass. Also, if windows cover 40% of the façade, there is adequate daylight in the room during 80% of the working hours.

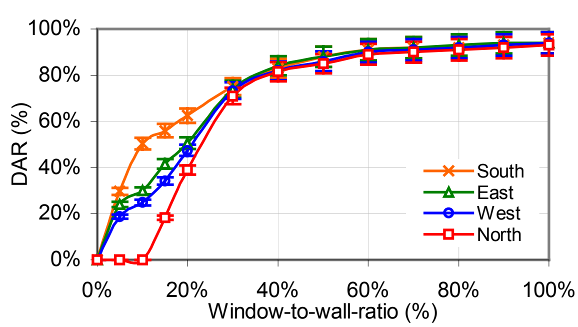

Figure 1. Daylight Availability Ratio as a function of glass ratio for different orientations.

Thermal considerations

Transient thermal studies were performed for heating and cooling design days using climatic data for Montreal. Solar gains, conduction gains, lighting and other internal gains were all taken into account. Fig. 2 shows that the difference in heating load between a south façade and a north façade does not exceed 13% and slightly increases with window-to-wall ratio. However, the situation is different for the peak cooling load (Fig. 3). Cooling load is again a linear function of relative window size but the effect of orientation is significant. Cooling load for a south-facing façade is practically two to three times higher than the load for a north-facing façade. The difference in load between north-facing facades and other orientations increases proportionally with window-to-wall ratio and reaches 66% if glass covers all the façade. The results of this analysis provide some important information: Figs. 2 & 3 show that even for heating-dominated climates cooling load is often higher than heating load (not for north-facing windows). Note that Montreal has a high percentage of sunny days per year, and also that cooling load is increased by common internal gains in office spaces. For the extreme case that window-to-wall ratio is 100%, heating load is only 56% of the cooling load value for a south-facing façade.

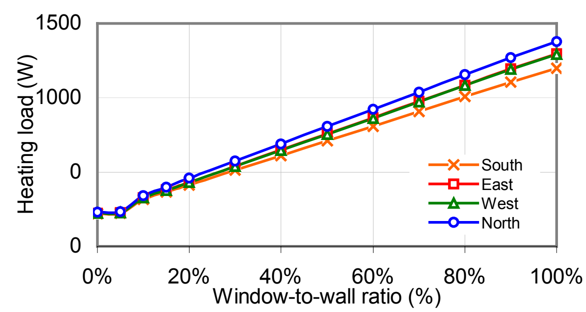

Fig. 2. Heating load as a function of glass ratio.

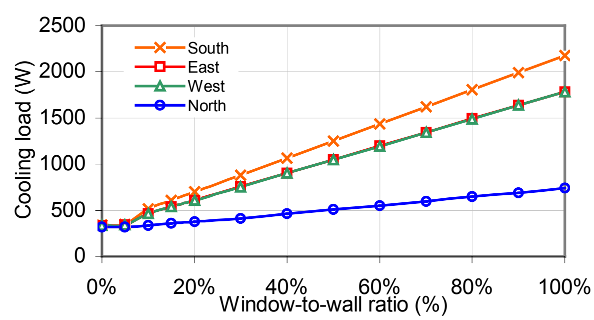

Fig. 3. Cooling load as a function of glass ratio.

The effect of window-to-wall ratio on annual energy consumption for a south-facing façade was also calculated using mean monthly outdoor temperatures and average clearness indices based on statistical data for the last 30 years (Table 1).

Table 1. Average annual energy consumption for heating and cooling for a south-facing office.

Window-to-wall Ratio (%)	Heating energy consumption (MJ)	Cooling energy consumption (MJ)
5%	4935	2200
10%	5381	2704
15%	5618	2914
20%	6064	3250
30%	6331	4104
40%	7430	4846
50%	8351	5602
60%	8885	6484
70%	9776	7366
80%	10548	8206
90%	11420	9018
100%	12152	9886

Electric lighting usage considerations

This section describes secondary measures for quantifying the effect of daylight utilization on energy consumption. The study included the effect on window-to-wall ratio 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. At this stage, the lights are assumed 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 using the results of daylighting simulation. For a specific glass ratio, the average annual electricity consumption for lighting will be equal to:

$$E_L = P_L \cdot A \cdot t_y \cdot (1 - DAR) \qquad (4)$$

where

P_L is the installed lighting power (W/m^2)

A is the total floor area (m^2)

t_y is the total number of working hours in a year (hr)

The annual average electricity consumption for lighting as a function of window-to-wall ratio for an unshaded window facing different orientations is shown in Figure 4. Lighting energy consumption drops rapidly when window-to-wall ratio increases. A comparison with no lighting controls (lights always on) is also shown. On/off operation of electric lights leads to 85% savings if 50% of a façade is glass. Reduced electric lighting operation due to daylight usage also results in reduction in cooling load and cooling energy consumption during the summer. Fig. 5 shows that cooling load is reduced by 15%-55% if daylighting is taken into account, assuming on/off operation of electric lights. If continuous dimming is used in conjunction with occupancy sensors, energy savings will be higher.

Criteria for selecting optimum window size

Based on the daylighting and thermal simulation results, the optimum glass ratio of the façade will be now determined. If not otherwise requested by the building designer/architect, the initial selection criterion should be maximization of daylight utilization. This approach is justified as follows:

- Comparing Fig. 1 and Figs. 2 & 3, the effect of relative window size in daylighting performance is higher than the effect on thermal loads, especially for small window-to-wall ratios.
- The effects of window thermal properties on daylighting and thermal performance were not considered yet. Peak loads and energy consumption would decrease if the window thermal resistance is increased. A separate sensitivity analysis revealed that, a 30% increase of window thermal resistance would lead to 10-%15% reduction in peak loads and 16%-25% reduction in heating and cooling energy consumption. However, the daylighting performance would not be affected, if clear glass is used.
- Finally, utilization of any kind of shading device will reduce peak cooling load, daylight availability will be significantly reduced.

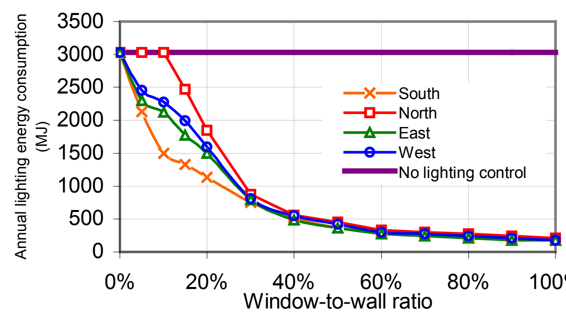

Figure 4. Annual electricity consumption for lighting assuming on/off control.

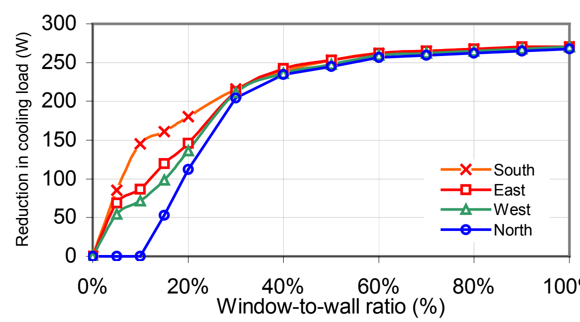

Figure 5. Reduction in peak cooling load due to on/off operation of electric lights (daylight utilization).

Simulation results reveal important information for selection of optimum window size. Figure 6 combines the results of the integrated daylighting and thermal analysis for the south-facing facade. As window-to wall-ratio increases, daylight usage increases and peak thermal loads and energy consumption also increase. The contradictive effect of daylight utilization on thermal loads is included in the graph. The curves reach a critical region, beyond which further increase in window relative size does not contribute to DAR, but would still increase peak thermal loads and average energy consumption for heating and cooling. Moreover, increasing window-to-wall ratio beyond this point would not result in significant reduction in electricity consumption for lighting, neither in reduction in peak cooling load due to minimized electric lighting usage. The critical region for the south-facing case is for window-to-wall ratios around 50%, as indicated by the black separation line in Figure 6. Subsequently, 50% window-to-wall ratio is selected as optimum window size for this case; it provides the space with adequate daylight for 85% of the working hours in a year (Figure 1). Also, by choosing this ratio, electricity consumption for lighting will be reduced by 85% -compared to no lighing control. Finally, cooling load will be reduced by 20% due to daylight utilization. At the same time, the thermal resistance of the window can be increased in order to further reduce loads and energy consumption.

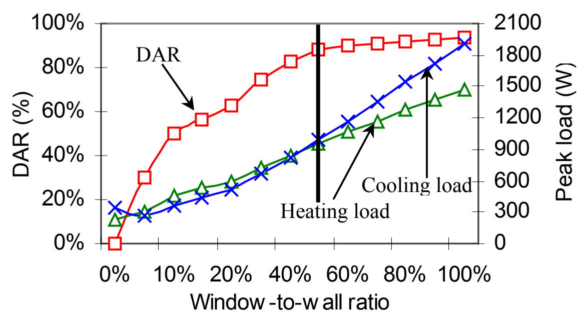

Figure 6. Critical window-to-wall ratio (black line).

THE IMPACT OF SHADING ON ENERGY EFFICIENCY AND COMFORT

The need for shading

The above analysis was done assuming that there is no shading provision. Nevertheless, daylight is only the visible portion of solar radiation. High solar gains will increase cooling load, but also reduce heating load during wintertime. In winter, glass temperatures usually fall below room air temperature, which may produce thermal discomfort for occupants near the fenestration. Moreover, problems associated with glare and visual discomfort are inevitable when direct daylight is transmitted inside. Shading provision is therefore necessary in order to prevent thermal and visual discomfort. An overview of daylighting/shading systems is presented in [12]. Shading devices are 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 [7,8,11,15,23], an integrated façade analysis is not applied at the early design stage, where critical decisions with small economic impact could lead to significant energy savings during the lifetime of the building. Advanced energy software and integrated simulation tools can handle these problems, but there still limitations in the process such as importing shading devices properties from existing databases - that do not allow extraction of optimum configurations. Furthermore, manufactures do not provide optical and thermal properties of shading/daylighting systems and thus these cannot be used with certainty in the above software engines. There is no systematic methodology for selecting optimal properties of shading devices, based on integrated design of facades. The Solar Attenuation Coefficients lately provided by ASHRAE [3] are based on measurements for specific values of profile angle, blind tilt angle. The most effective means of establishing fenestration annual energy performance is through detailed, dynamic, hourly simulation for the specific building and climate of interest.

Shading parameters affecting energy performance of buildings

The effect of shading on visual and thermal comfort and energy efficiency is determined by three main parameters: (i) the type of shading device used (ii) the thermal and optical properties of the shading device and (iii) the considered control of the shading device (if any). The selection of type of shading device is always the first step. This depends on the building type, aesthetics, climate, orientation, functionality and cost. In practice, two main types of shading devices are used in office buildings nowadays: roller shades and venetian blinds. Roller shades can ensure privacy and transmit diffuse light in the space. Venetian blinds allow partial view to the exterior and redirect daylight depending on their tilt angle. The second step is the selection of optical and thermal properties for the shading device. For any kind of system, this would initially determine the impact of shading on the interior. The effect of these properties on lighting, heating and cooling energy consumption, and on visual and thermal comfort has not been investigated. Instead, manufacturers provide products with standard properties and these are installed on building facades. In this way, the design is not optimized, but designer's choices are limited within a variety of available models.

The third and final consideration is the control of the shading system. A study about multiple shading control strategies and criteria showed the complexity of the problem [14]. The selection of control strategy plays a major role in the determination of interior 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. Futhermore, in order to be consistent with the integrated design process, the type of control strategy has to be decided simultaneously with the type of shading device used and with the selection of its optical and thermal properties -and vice versa. This iterative process shall lead to overall optimization of shading systems design and operation, with respect to energy efficiency and human comfort.

An example-roller shades

Generally, roller shades ensure privacy and occupants can have the choice of opening and closing them whenever they want. This may lead to false operation and cause visual discomfort and overheating. If roller shades are automated, they can be kept open during overcast days for maximization of daylight utilization and outward view. During sunny days, they should close, to eliminate glare and transmit diffuse daylight in the room. The amount of transmitted daylight will depend on the visible transmittance of the device. Because major solar gains are excluded, a reduction in peak cooling load is also expected. However, for very small values of transmittance, daylight usage will be significantly reduced and electricity consumption for lighting will increase. Thus, internal gains will be increased and also view to outside will be minimized. A transient integrated daylighting and thermal analysis for the shade surface will lead to selection of optimum properties and control. The effect of an exterior roller shade optical and thermal properties and type of control in energy efficiency and comfort in a south-facing perimeter office is investigated next as an example. The transmittance can vary continuously from 0% to 100% in the model (practical limits are much smaller). A comparison between two control options is made: (i) roller shade is always closed to ensure privacy (ii) roller shade is closed during sunny days to prevent from glare and overheating, and open during overcast days, for maximization of outward vision, daylight utilization, and reduction in lighting consumption.

First, the effect of shade transmittance on daylighting performance is studied. Modifying Eq. *(1)*, the total amount of transmitted daylight will be equal to:

$$G(n,t)=[E_d(n,t)\cdot\tau_d(n,t)+E_b(n,t)\cdot\tau_d(n,t)]\cdot\tau_{rs} \qquad (5)$$

where τ_{rs} is the visible transmittance of the roller shade. Work plane illuminance calculations are repeated and annual DAR is computed as a function of roller shade visible transmittance for a south-facing office (Fig. 7).

Keeping the shade closed results in 30% reduction in annual usage of daylight, as opposed to simply control it. For transmittance values higher than 20%, there is no further increase in daylight usage. The simultaneous impact of shade transmittance on annual lighting energy consumption including daylighting utilization is presented in Fig. 8. A 69% reduction in electricity consumption is achieved if the shade is controlled in conjunction with electric lights. No further reduction in energy consumption occurs for transmittance values higher than 20%. The effect of shade transmittance on peak heating and cooling load is shown in Fig. 9. Cooling load is dramatically reduced by 41%-68% if lights are not controlled and 52%-68% if lights are controlled (on/off), compared with the non-shading scenario. Thus shading device properties and control should be taken into account when sizing the cooling system, at the early design stage. However, cooling load decreases suddenly by 28% for transmittance equal to 15%, because daylight availability is then enough for electric lights to start the on/off operation, thus reducing cooling load.

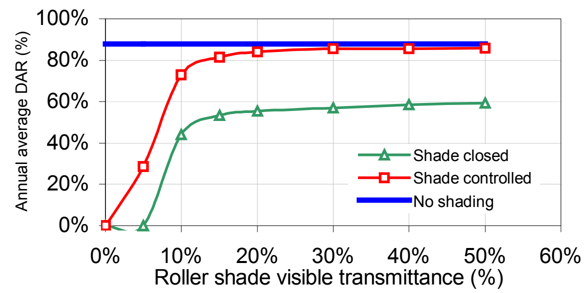

Figure 7. The effect of roller shade transmittance on annual average DAR for a south-facing façade.

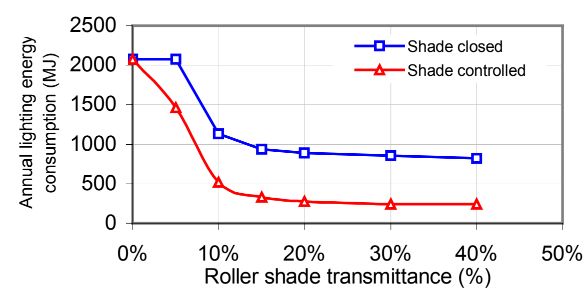

Figure 8. Annual electricity consumption for lighting assuming on/off operation.

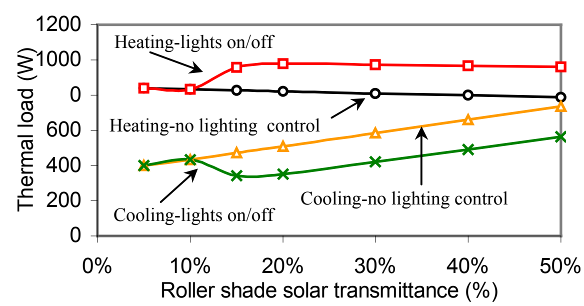

Figure 9. The effects of roller shade transmittance and electric lighting control on heating and cooling load.

The last part presents the effect of shade transmittance on average annual energy consumption for heating and for cooling. Fig. 10 shows the results of the integrated simulation for the case of no shading control, with on/off operation of electric lights. The effect of daylight utilization on annual heating, cooling and lighting energy consumption is included. The cooling curve takes into account internal lighting gains but also reduction in cooling energy consumption due to reduced lighting operation. The curve showing the sum of annual cooling and lighting energy consumption is of special interest. It decreases up to $\tau_{rs}\approx 15\%$ and then keeps increasing. This is a key indicator for identifying the optimum transmittance of the shade. Optimum energy performance is achieved when daylighting benefits due to reduced electric lighting usage and thus due to reduction in cooling load exceed the increase in energy consumption due to extra solar gains. Selection of optimum shading device transmittance should be made with respect to visual comfort also (Fig. 7). For $\tau_{rs}>15\%$, daylight utilization is not practically increasing. Therefore the optimum shade transmittance is selected 15% for this case. The exact optimum value, τ_{opt}, may be calculated from:

$$\left.\frac{\partial E_{Cooling+Lighting}}{\partial \tau}\right|_{\tau=\tau_{opt}} = 0 \qquad (6)$$

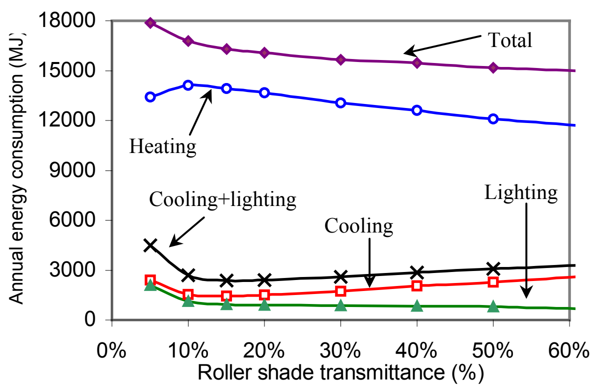

Figure 10. Annual energy consumption for heating, cooling and lighting as a function of shade transmittance. Roller shade is kept closed and electric lights are controlled..

If the shade is controlled, the calculation of annual energy consumption is done in a different way. Thermal loads and daily energy consumption are computed separately for clear and overcast days of each month. Then the average monthly energy consumption for heating, cooling and lighting is calculated as a weighted average, based on the number of clear and cloudy days in each month. The annual energy consumption is finally calculated by adding the monthly components. The same procedure is followed when calculating annual DAR in Fig. 7 and it reveals the sensitivity of results in climatic parameters and orientation. The results are shown in Fig. 11. Optimum energy performance is realized for shade transmittance close to 14%. For the optimum value of transmittance calculated, the total annual energy consumption is reduced by 7% if the shade is controlled. Moreover, shading control results in 30% increase in DAR ,compared with a closed shade. This is translated as increased productivity and improved visual quality.

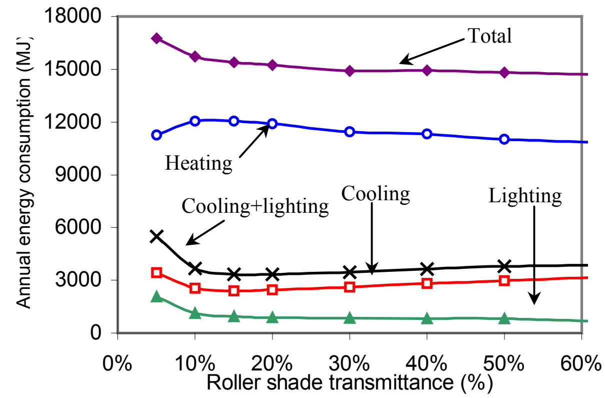

Figure 11. Annual energy consumption for heating, cooling and lighting as a function of shade transmittance. Roller shade is controlled in conjunction with electric lights.

SUMMARY AND CONCLUSION

This paper presented a simulation-based integrated thermal and daylighting analysis for office building facades. The objective was to optimize fenestration performance in perimeter office spaces, with respect to energy efficiency and human comfort. The effect of window-to-wall ratio on visual and thermal performance and electric lighting usage in perimeter spaces was investigated and guidelines for choosing the optimal glass ratio were discussed. The impact of simple on/off operation of electric lights on energy performance was also studied. Daylighting and thermal effects were taken into account, but the dominant initial criterion was 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. The optimum window-to-wall ratio for a south-facing façade was found 50%. The need for shading and the complexity of interactions between daylighting and thermal parameters when designing and controlling a shading device were discussed in detail. The type of shading device used, its optical and thermal properties and the control of the shading system will determine visual and thermal indoor conditions and energy performance. The type of control should be decided simultaneously with the selection of shading device type and properties using an integrated thermal and daylighting approach.

An exterior roller shade was used as an example of integrated analysis. Peak heating and cooling load, annual average energy consumption for heating, cooling and lighting and daylight utilization were all taken into account and the effects of daylight usage on energy performance were used to attain an optimal value for the shade transmittance. Simultaneous control of a shading device and a lighting system could lead to minimization of energy consumption for lighting and cooling, reduction in HVAC system size and maximization of daylight utilization. This type of analysis should be done during the early design stage, when critical decisions will have a major impact on energy performance during the lifetime of the bulding. Advanced simulation software (*e+, ESP-r*) could help in building a generalized and systematic method for fenestration and shading design optimization, based on integrated daylighting and thermal analysis.

ACKNOWLEDGEMENTS

Support of this work from ASHRAE and NSERC is gratefully acknowledged.

REFERENCES

1. F.Aleo, S.Sciuto, R Viadana, "Solar transmission measurements in outdoor conditions of non-homogeneous shading devices", European conference on energy performance and indoor climate in buildings, Lyon, France, pp. 1074-1079, 1994.

2. M. Andersen, M. Rubin, J-L.Scartezzini, "Comparison between ray-tracing simulation and bi-directional transmission measurements on prismatic glazing", Solar Energy 74 (3), pp. 157-173, 2003.

3. ASHRAE ASHRAE Handbook-Fundamentals (2001).

4. A. Tzempelikos & A. K. Athienitis, "A Methodology For Detailed Calculation Of Room Illuminance Levels And Light Dimming In A Room With Motorized Blinds Integrated In An Advance Window", eSim2001 National Building Simulation Conference, Ottawa, Canada, 2001.

5. A. Beck, W. Körner, O. Gross, J. Fricke, "Making better use of natural light with a light-redirecting double-glazing system", Solar Energy 66 (3), pp. 215-227, 1999.

6. CIE, "Standardization of luminous distribution on clear sky", Pub. 22, Paris, France, 1973.

7. S. Citherlet & J-L. Scartezzini, "Performances of advanced glazing systems based on detailed and integrated simulation", Status Seminar, ETH-Zurich, 2003.

8. J.A. Clarke, M. Janak, P. Ruyssevelt, "Assessing the overall performance of advanced glazings systems", Solar Energy, 63 (4), pp. 231-241, 1998.

9. M. Collins, S.J. Harrison, D.Naylorm, P.H. Oosthuizen. "An interferometric study of convective heat transfer from an irradiated complex window assembly", IMECE2001, New York, pp. 1-13, 2001.

10. L. Heschlong, "Daylighting and human performance", ASHRAE journal, 44 (8), pp. 65-67, 2002.

11. R. Johnson, R. Sullivan, S. Selkowitz, C. Conner, D. Arasteh , "Glazing energy performance and design optimization with daylighting", Energy & Buildings No. 6, pp. 305-317, 1984.

12. M. Kischkoweit-Lopin, "An overview of daylighting systems", Solar Energy 73 (2), pp. 77-82, 2002.

13. S.A. Klein & J.A. Duffie, "Estimation of monthly average diffuse radiation", ISES annual meeting -American section, pp. 672, 1978.

14. E. Lee & S.E. Selkowitz, "The design and evaluation of integrated envelope and lighting control strategies for commercial buildings", ASHRAE Transactions 101 (1), pp. 326-342, 1995.

15. E.S.Lee, D.L. DiBartolomeo & S. Selkowitz, "Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office", Energy and Buildings No. 29, pp. 47-63, 1998.

16. W. Lorenz, "A glazing unit for solar control, daylighting and energy conservation", Solar Energy 70 (2), pp. 109-130, 2001.

17. L. Molina, R. Maestre, E. Lindawer, "A model for predicting the angular dependence of the optical properties of complex windows including shading devices", PLEA2000, UK, pp. 765-770, 2000.

18. P. Pfrommer, K.J. Lomas, C. Kupke, "Solar radiation transport through slat-type blinds: a new model and its application for thermal simulation of buildings", Solar Energy 57 (2), pp. 77-91, 1996.

19. C.F. Reinhart and O. Walkenhorst, "Validation of dynamic Radiance-based simulations for a test office with external blinds", Energy and Buildings No. 33, pp. 683-697, 2001.

20. S. Rheault and E. Bilgen, "Heat transfer analysis in an automated blind window system", Journal of Solar Energy Engineering, Vol. 111, pp. 89-95, 1989.

21. J.L.J. Rosenfeld, J. Breitenbach, S. Lart, I. Langle, "Optical and thermal performance of glazing with integral venetian blinds", Energy and Buildings No. 33, pp. 433-442, 2001.

22. A. Tzempelikos & A.K. Athienitis, " Modeling and evaluation of a window with integrated motorized venetian blinds", ISES2003 World Congress, Gotenburg, Sweden, 2003.

23. A. Tzempelikos & A.K. Athienitis, "Simulation for façade options and Impact on HVAC system design", IBPSA, Netherlands, 2003.

24. Tzempelikos A. & Athienitis A.K.. 2002. Investigation of lighting, daylighting and shading design options for new Concordia University engineering building. eSim2002 National Building Simulation Conference, Montreal, Canada, pp. 177-184.

25. A.K. Athienitis & A. Tzempelikos, "A Methodology For Simulation Of Daylight Room Illuminance And Light Dimming For A Room With A Controlled Shading Device", Solar Energy, Vol. 72 (4), pp. 271-281, 2002.

26. E. Vartiainen, K. Peippo, P. Lund, "Daylight optimization of multifunctional solar facades". Solar Energy 68(3), pp. 223-235, 1999.