IMPACT OF SHADING CONTROL AND THERMOSTAT SET POINT CONTROL IN PERIMETER ZONES WITH THERMAL MASS

Ying-Chieh Chan, Athanasios Tzempelikos
School of Civil Engineering, Purdue University, West Lafayette, Indiana, USA
E-mail: ychan@purdue.edu, ttzempel@purdue.edu

ABSTRACT

This study is focused on the impact of shading control and thermostat set point control on daylighting metrics, glare evaluation and energy consumption for perimeter office spaces (zones around perimeter). State-of-the-art and new control strategies for roller shades are summarized and their effect is analyzed for spaces with thermal mass in two different climates. Open/closed and proportional control based on outdoor incoming solar radiation, transmitted illuminance or work plane protection from sunlight and glare are studied using an integrated thermal and daylighting model which is based on an implicit finite difference thermal network approach (thermal part) and a hybrid radiosity/ray-tracing module (lighting part) linked together at each calculation time step. Set back strategies and flexible thermostat set points are also discussed. Annual results of daylighting metrics, glare indices and energy consumption are presented for the considered control strategies as well as validation of results with experimental measurements.

INTRODUCTION

Building control strategies are crucial for improving energy performance and indoor environmental quality. This paper is focused on two commonly used applications - the thermostat set point control and shading control –using roller shades as a typical case. Both of these parameters have an impact on cooling and heating energy use as well as on occupants' thermal comfort. Also, shading control impacts daylighting performance, lighting energy consumption and occupants' visual comfort. In addition, electric lighting operation directly affects internal heat gains which are often a significant part of the cooling load, especially for office buildings. Therefore, the effects of the above control parameters are inter-related.

Thermostat set point control is widely used and easy to implement. One of the most common types of control is set point setback. For example, during the heating season, a lower set point could be set at night to allow the temperature in the office to lower during non-office hour -when there is no one in the room. However, it might increase the peak load during the daytime. The other common type of thermostat control is to allow a wider, more flexible range of set points during office hours. The strategy is based on the concept of adaptive thermal comfort (Nicol and Humphreys 2002). Researchers claimed that the occupants' preferred temperatures are varied due to different outdoor environmental conditions (Yao, Li et al. 2009; Orosa and Oliveira 2011). This paper discusses the energy savings potential of these two strategies by applying them on building perimeter zones with different thermal mass levels.

The other target of this paper is to investigate the impact of shading control strategies. Roller shades are often used as a common shading solution in office building to ensure privacy and prevent glare. Several studies have shown the potential for energy savings by applying roller shades (Selkowitz and Lee 1998; Tzempelikos and Athienitis 2007; Hviid, Nielsen et al. 2008; Shen and Tzempelikos 2012). However, in reality, most occupants are fairly inactive (O'Brien, Kapsis et al. 2013) when automated operation is not enabled and that causes poor daylight penetration and reduced energy performance. Automated control is a possible solution to enhance the positive effect of shading. Nevertheless, inappropriate operation of shades could cause uneven illuminance distributions which increase visual discomfort probability (Kim, Kim et al. 2007) or even increase energy use. The question becomes: “how to achieve a sense of balance between energy performance and occupant comfort”. Zhang and Lam (2010) conducted a case study regarding sky conditions and room conditioning modes. Wankanapon and Mistrick (2011) presented an analysis using shading controls based on different solar radiation levels on the window. Correia da Silva, Leal et al. (2012) reviewed different criteria used to establish the occupants' requirements for visual comfort in office buildings that include luminance, illuminance, solar radiation, and discomfort indexes which were hard to defined due to the complexity of human psychology. The energy performance using these criteria was also evaluated in this study. Several indicators were developed to evaluate the visual comfort especially under the daylight conditions including CGI (Einhorn 1969), DGI (Osterhaus 2005), and DGP (Wienold and Christoffersen 2006). However, there is no consistency of the shading control criteria until now. It is highly dependent on location, orientation, window size, room size, glazing and shading properties. This work investigates the impact of different control strategies for a private office.

SIMULATION MODEL

Thermal model

The thermal model is based on a one-dimensional implicit finite difference thermal network to predict the transient thermal behaviour including conduction, convection, and radiation. Each surface of the building is presented as a node set with thermal mass. For the surfaces with several thermal mass layers or heavy thermal mass, the layer is divided into small sections connected with appropriate resistances. Each thermal mass layer is separated into at least three control volumes. Convective heat transfer coefficients for both exterior and interior surfaces are obtained using ASHRAE (2009) recommended equations. The thermal model for the glazing-shading system is based on the ISO 15099 (2003) method, including the convection effects inside the shade-gap cavity. When the shades are closed, there is usually a temperature difference between the air in the gap and the indoor air temperature, which drives an airflow associated with heat gain or heat loss. The radiation part is modelled using real geometry.

Daylighting model

The sky illuminance distribution is derived from the Perez et al. model (1987). The interior illuminance model is a combination of ray tracing and radiosity methods. The projection areas of windows or windows with roller shades on the interior and work plane surfaces are traced from the position of sun, which is then treated as an additional surface with initial luminous exitance in the radiosity calculations. Radiosity method assumes that all interior surfaces are Lambertian, which requires a calculation of view factors between surfaces. If specular surfaces are involved, more advanced methods can be used as described in Chan and Tzempelikos (2012). The final illuminance distribution on interior surfaces, work plane surfaces, and the illuminance values on vertical reference point in the middle of the room (used in glare calculations) are obtained from the results of combining these two methods.

Glare evaluation model

To evaluate glare, daylight glare possibility (DGP) is computed which is an index developed with a daylighting focus, supported by experimental evaluation (Wienold and Christoffersen 2006). It is a function of the vertical (eye) illuminance as well as of glare source luminance as showed in Eq. (1).

$$\boldsymbol{DGP} = 5.87\times10^{-5}\boldsymbol{E}_v + 9.18\times10^{-2}\log(1+\sum_i \frac{\boldsymbol{L}_{s,i}^2\omega_{s,i}}{\boldsymbol{E}_v^{1.87}\boldsymbol{P}_i^2}) + 0.16 \quad (1)$$

where EV the vertical illuminance on the eye level, Ls,i is luminance of glare source (i), ωs,i is solid angle of glare source, and P is the position index of glare source. In order to calculate vertical illuminance, a reference point and a view direction vector are placed in the simulated space to represent the occupant's approximate position of the eyes and viewing directions. The entire room (both window and opaque surface) is cut into small segments (each surface is divided into 400 segments in this study) and those segments are evaluated separately. Solid angle, position vector, and the angle between the line of sight and the lines connecting view points and small segments are all pre-calculated. If the angle is higher than 78°, the segment is outside the occupant's field of view. For segments inside the field of view, we need to determine if the luminous source is a glare source. In this paper, the glare source is defined as having 4 times the average work area luminance, which is defined as a 0.2m x 0.2m rectangular in front of the occupant's position at the height of 0.8m. The luminance distribution of the window can be estimated by computing the diffuse sky and ground illuminances and direct illuminance from the sun. The diffuse illuminance from the sky is assumed as uniform with incoming directions from 0 to 90 degrees, and the ground diffuse illuminance is assumed as uniform with incoming direction from -90 to 0 degrees. The position index is calculated with different equations depending on the position of the source with respect to the line of sight. The part above the line of sight uses the model proposed in IES handbook (1984) and the part below the line of sight uses the model established by Iwata and Tokura (1990). To calculate vertical illuminance, the amount of direct illuminance that directly strikes on the point representing the eye position is computed based on the sun's position and the illuminance data obtained from simulation or measurements. Diffuse illuminance is calculated from the configuration factors between other surfaces inside the room and the virtual point as processed in the radiosity method.

Model description and control set points

The baseline model is a 4m by 4m by 3m high perimeter office with a south facing window. The window size is 2m (length) by 1.6m (height) and the window-to-wall ratio is 40%. The glazing system is a double-glazed clear glass (transmittance is 0.781 for visible and 0.606 for solar at normal incidence). An interior roller shade with a reflective outside surface (76%) and 7% visible transmittance is used. The gap width between the glass and the shade is 0.12m and the gap on the four perimeter sides is 0.02m. The reflectance of interior floor, ceiling and walls are equal to 45%, 80% and 50% respectively. The installed lighting power density is 10 W/m^2 and electric lights are continuously dimmable (1-100%). Occupant internal heat gains are equal to 70W. Table 1 summarizes the combinations of modeling and control variables and set points.

Table 1
Control variables and set points considered

Climate (location)	Floor Thermal Mass Levels	Thermostat Set Point (Office/Non-office hours)	Shading Control Criteria/Set points
Philadelphia Phoenix	0.1 m -light 0.2 m -heavy	22-24/22-24 ^{0}C 20-26/20-26 ^{0}C 22-24/18-28 ^{0}C	Always Open/NA Always Closed/NA “**Solar**”: Total Solar Radiation on Window/189 W/m^2 “**Transmitted**”: Transmitted Illuminance through Window/15000 lx “**WP**”: Work Plane Protection “**WPS**”: Work Plane Protection and Extra Criteria for Sky Conditions/8000/20000 lx

The shading control methods listed in Table 1 include two baseline cases (open and closed shades without control) for reference and four different control strategies. Shades can be controlled based on total solar radiation incident on the window: in this case, 189 W/m^2 is used as the set point as suggested by Wankanapon and Mistrick (2011); different studies assume different set points for total incident or direct solar radiation and for transmitted solar radiation. The second control method uses transmitted illuminance through the window as the control criterion to bypass glazing properties. In this study, 15000 lx is used as the set point to close shades (too bright) as suggested by Zhang and Lam (2010). Different set points can be defined to close and open shades depending on space geometry and shading properties, that can be obtained by measurements or simulation (Tzempelikos and Shen, 2013). Another control strategy used is “work plane protection” in which shades are controlled to intermediate positions to prevent direct sunlight from falling on the work plane area. In this way, daylight maximization is desired since the shades never close completely, and they are often completely open if the window does not see the sun. In every time step, the shade position is proportionally controlled and determined by:

$$H_{so} = D_w \tan(\Omega) \qquad (2)$$

where $\boldsymbol{H_{so}}$ is the shade opening height relative to floor, $\boldsymbol{D_w}$ is the distance from window to working area and $\boldsymbol{\Omega}$ is profile angle of the sun. In this study, $\boldsymbol{D_w}$ was set to 1.5m. This control method requires consideration of extra (sunlit) sub-surfaces in the room which need to be taken into account in the thermal and lighting modules.

The last control strategy is similar to the previous one but with addition of extra criteria for (i) further protection of excessive daylight and (ii) set points for opening shades completely under low sky illuminance levels. These set points are based on correlations between transmitted and work plane illuminance and can be determined by parallel simulation runs for different sky conditions. For the considered space, shades are proportionally controlled but will close completely when transmitted illuminance exceeds 20000 lx; they will fully open when transmitted illuminance falls below 8000 lx. Appropriate thresholds and dead bands can be defined for more conservative operation.

RESULTS AND DISCUSSION

Daylight autonomy and glare evaluation

Daylighting metrics such as daylight autonomy and useful daylight illuminance indices (Nabil and Mardaljevic, 2005, 2006) provide useful insights for evaluation of daylighting performance. Daylight autonomy (DA) was calculated for the entire work plane grid during working hours (9am-5pm) for the entire year. Figs. 1 and 2 present the DA spatial distribution for Philadelphia and Phoenix using the four different shading control methods.

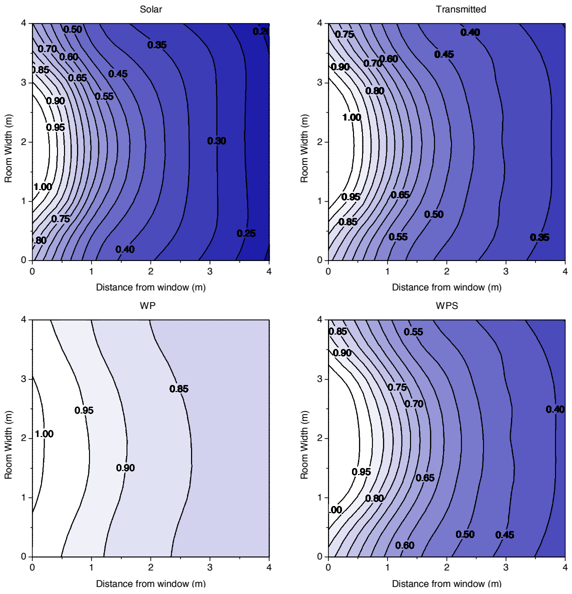


Figure 1 Spatial Distribution of Average Annual Daylight Autonomy (%) for the private office in Philadelphia

The DGP index is calculated based on Eq. (1), considering all glare sources in the field of view. For the “WP” method, except for the window as a source, this requires the calculation of the luminance of sunlit projections on the floor (which vary in intensity and size with time) and simultaneous computation of solid angle and position index for every segment –for every simulation time step. The averaged annual values of DA and DGP higher than 45% are shown in Table 2 using different shading control strategies for both Philadelphia and Phoenix. Naturally, the higher the DA, the higher the probability of visual discomfort. However, relatively "optimal" solutions can be achieved with proper selection of set points (and shading properties which are not discussed here). For Philadelphia, the "solar" control results in minimized DGP values while DA reaches 46%. On the other hand, the "WP" method allows daylight maximization (DA=87%) but also results in excessive daylight for a significant portion of the time and high vertical illuminance on the eye, as well as uneven illuminance distributions and high contrast due to the sunlit projections, all of which increase DGP to values higher than 45% for 56% of the working hours. The additional set points considering sky conditions ("WPS") eliminate the significant glare issues while allowing more daylight than the "solar" method. Finally, the "transmitted" method provides satisfactory results and it might be considered a more appropriate criterion for shading control than "solar" whenever glare is of interest.

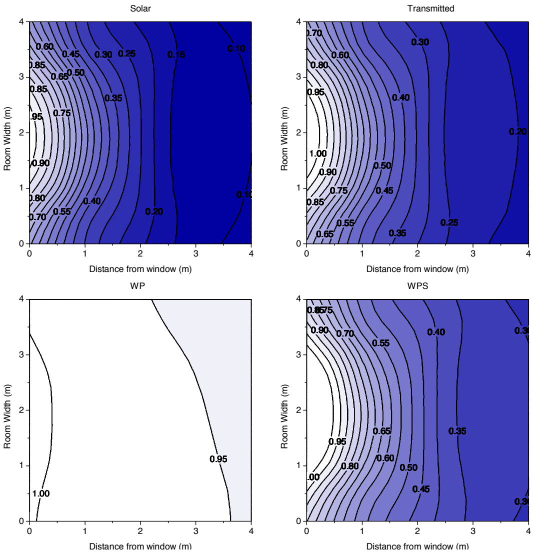


Figure 2 Spatial Distribution of Average Annual Daylight Autonomy (%) for the private office in Phoenix

The differences between Philadelphia and Phoenix are evident and are largely due to different solar and profile angles. For example, under high angles, the shades will remain mostly open using "WP" control, which will cause excessive daylight transmission and glare problems –and thermal implications as discussed later. For this location, it is important to control shades efficiently using either transmitted illuminance or "WPS". DGP with the control based on transmitted illuminance shows a significant difference between these two locations also because of the different solar angles (the direct illuminance on a vertical plane at approximately eye height is much lower in Phoenix).

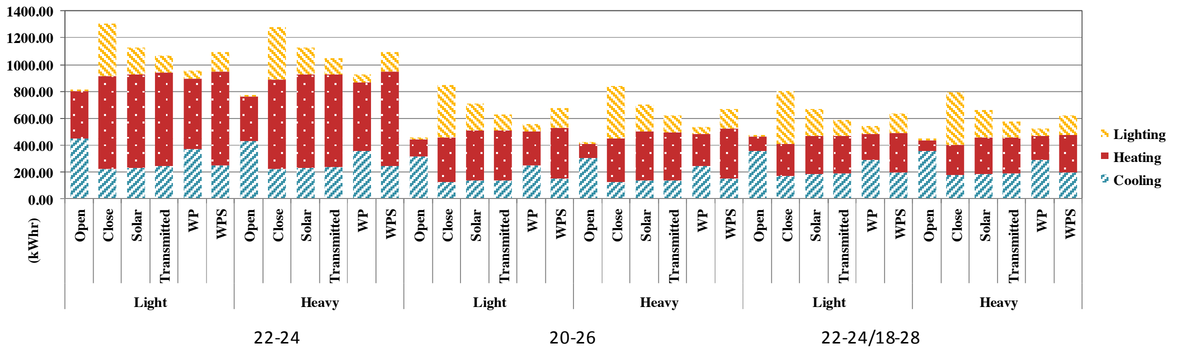
Energy use results –mixed climate

Figure 3 shows the site annual energy consumption for Philadelphia for all studied cases (shading control methods, thermostat set points and floor thermal mass levels). Heating and cooling loads obtained from the transient model were used with a cooling system (COP=3.4) and a heating system (COP=0.8). Having the shades completely open results in lower energy use but this is not a realistic case (due to glare and overheating problems) and is shown only for reference. Heating and cooling energy use are quite similar for the closed, "solar" and "transmitted" shading controls (for each thermostat control case). These methods prevent excessive solar gains when the shades are closed. It is worth commenting on the heating energy use results: "solar" and "transmitted" strategies result in slightly higher heating energy than "closed" shades although some solar gains are allowed. This is explained by resulting lighting heat gains for these cases (more daylight is present so they are lower compared to closed shades) which are higher than incoming solar gains and therefore the heating load is increased accordingly. It is important to study these interactions between daylighting benefits and thermal requirements for balancing lighting energy use, solar and internal heat gains while considering comfort parameters that vary depending on the shading control strategy used. Lighting energy use plays a key role when comparing the shading control strategies and although "WP" reduces total energy use, it cannot always avoid glare problems.

The energy savings of applying a thermostat set back strategy during non-office hours or a more flexible set point limit are both noticeable compared to the original case (22-24 °C constant). The flexible set point strategy has a clear impact on cooling energy savings while the set back strategy shows a good ability to decrease heating load. Regarding thermal mass levels, the actual temperature fluctuations might be reduced a bit when looking at sub-hourly data, however the total effects are quite small. There is a small effect of having a floor mass layer thicker than 0.1m, however that impact is almost eliminated for 0.2m thick mass and therefore there is no need to invest in more massive layers to shift or reduce loads. This is also shown in Fig. 4 that presents peak heating and cooling loads for all the studied cases. The increase in peak loads using the set back strategy is due to the extra energy needed in the morning to heat or cool the space before the occupants arrive. Flexible set points provide the best results but adaptive comfort limits needs to be further studied.

Table 2
Annual DA and DGP Results with different Shading Control Strategies for the two locations

	Always Open	Always Closed	Solar Radiation	Transmitted Illuminance	Workplane Protection	WP with Sky Condition
Philadelphia						
DA	0.97	0.18	0.46	0.64	0.87	0.57
DGP>45%	0.65	0.02	0.06	0.23	0.56	0.13
Phoenix						
DA	0.99	0.18	0.31	0.40	0.97	0.52
DGP>45%	0.70	0.00	0.01	0.02	0.62	0.08



**Solar – solar radiation on window (189W/m^2)*
**Transmitted – transmitted iluuminance (15000 lux)*

**WP – work plane protection*
**WPS – work plane protection /w sky conditions consideration (open: 8000/close: 20000 lux)*

Figure 3 Site energy consumption for Philadelphia

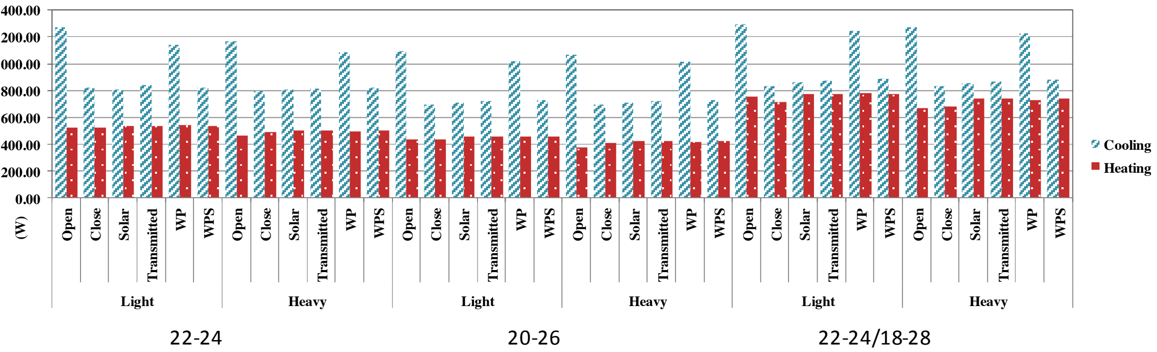


Figure 4 Peak Heating and Cooling Load for Philadelphia

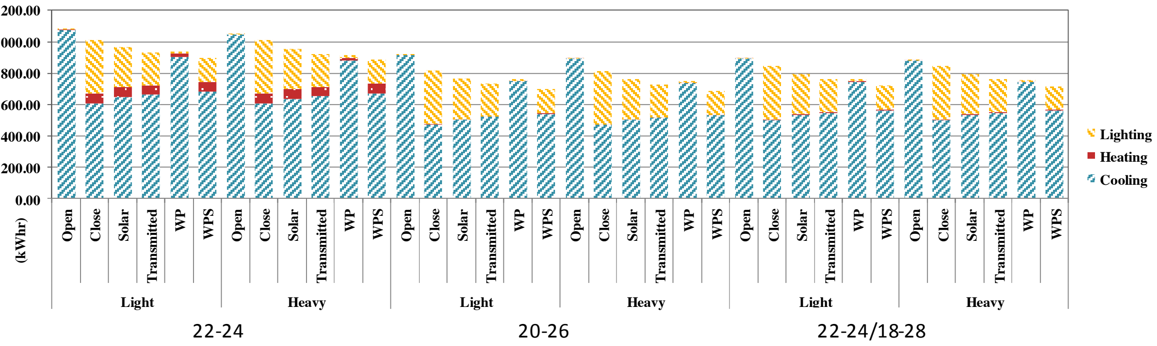


Figure 5 Site energy consumption for Phoenix

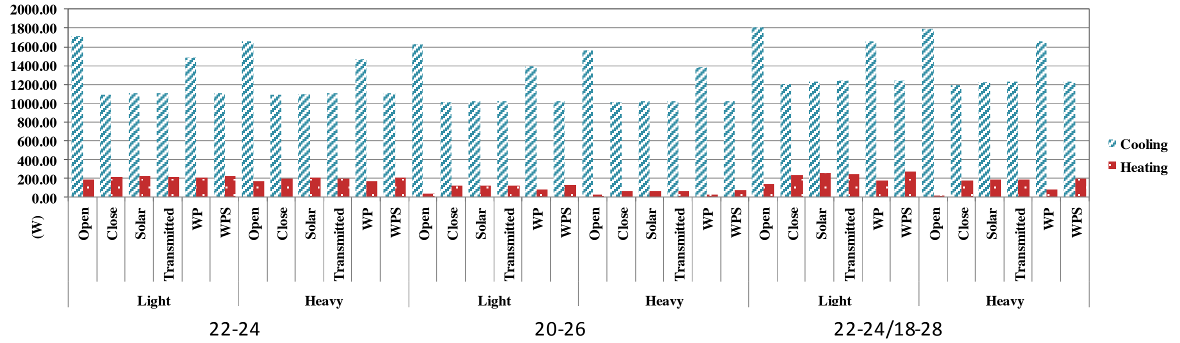


Figure 6 Peak Heating and Cooling Load for Phoenix

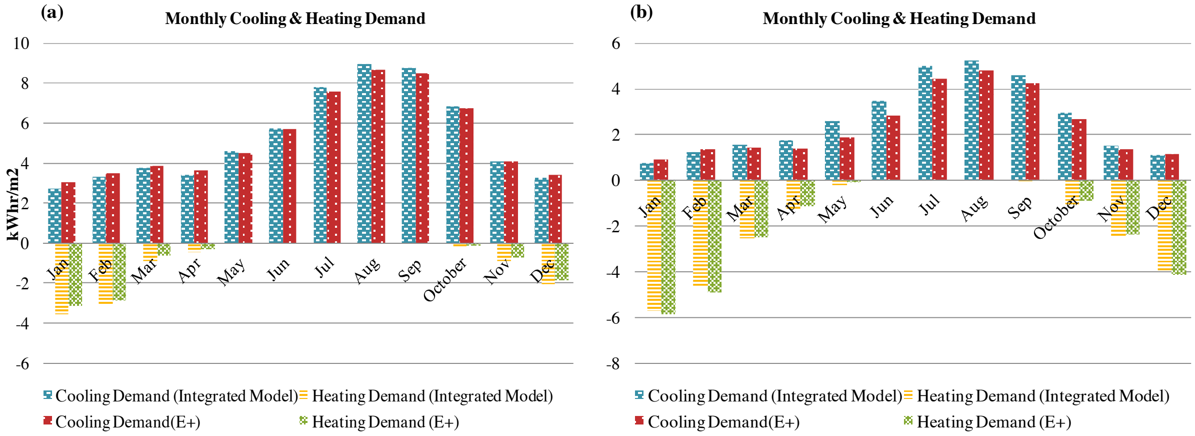


Figure 7 Comparison between simulation results and EnergyPlus heating and cooling results for (a) Open Shades (b) Closed Shades

Energy use results –hot climate

Figure 5 presents the site annual energy consumption for Phoenix. This is a cooling-dominated climate and heating is minimal. Unlike the results for Philadelphia, the best shading control strategies here are using transmitted illuminance or "WPS". For this location, a balance between lighting operation, daylight use and cooling energy use can be achieved using appropriate façade controls. The effects of thermostat set point strategies are similar to above, however in this case the setback option does not require extra energy for heating the space and the results are closer.

Comparison with EnergyPlus and validation of results

To verify our simulation results, a comparison of baseline cases for Philadelphia with EnergyPlus was implemented. As showed in Figure 7, the results for open and closed cases are in good agreement. The main difference happened in cooling energy demand during spring and summer, possibly due to differences between our hybrid ray-tracing and radiosity model and the daylighting model used by EnergyPlus, which affect internal heat gains - especially for cooling results. Validation with experimental results for different control strategies can be found in Tzempelikos and Shen (2013).

To further validate simulation results, several cases were tested in full-scale experimental facilities at the Purdue Architectural Engineering Labs (Latitude 40°N, Longitude 87°W). Two identical side-by-side office spaces (5m x 5.2 m x 3.4 high) with one exterior façade were used, each equipped with interior automated roller shades. Different shading controls were applied to each space under the same exterior conditions while monitoring the effects on indoor air temperature, surface temperatures and work plane illuminance values over two rows of sensors (close to the façade and deeper in the room). Representative results are shown in Figs. 8 and 9 for three successive days.

In Figure 8, the measured and simulated indoor air temperatures are simultaneously compared for the "transmitted" and "WPS" control strategies under the same exterior conditions (also plotted for reference). WPS results in higher indoor air temperature as expected since shades are open for longer periods of time. The maximum temperature difference noticed is 2^{o}C. In general, the simulation results agree with the experimental data and can accurately capture the effects of different shading control strategies. The

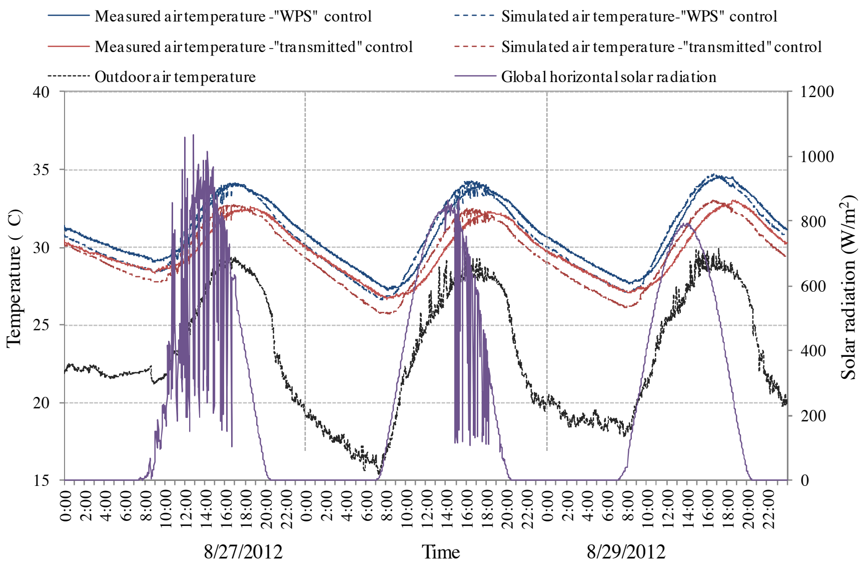


Figure 8. Simultaneous comparison of measured and simulated indoor air temperatures for "transmitted" and "WPS" controls during three successive days

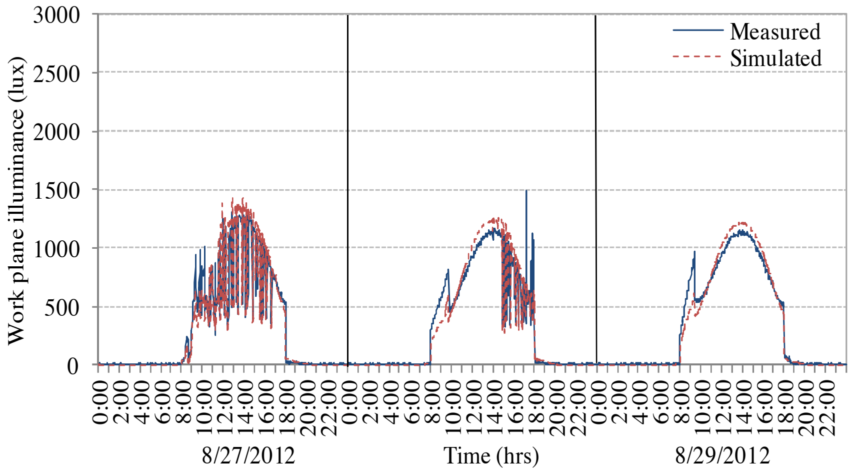


Figure 9. Comparison of measured and simulated work plane illuminance values using "WPS" control at 3m from the façade.

small time lag noticed is attributed to some uncertainties in the floor and ceiling material properties.

Figure 9 compares the measured and simulated work plane illuminance values for sensors (points) placed 3m from the facade using the "WPS" control –since this is the most difficult case to model. The simulation results reflect the variation of lighting conditions in the space quite well.

CONCLUSION

This study investigated the balance between lighting, heating, and cooling energy consumption in perimeter private office spaces with automated interior roller shades. Four shading control strategies were studied along with different thermostat set point controls and floor thermal mass levels. The impact of control criteria and set points on daylighting metrics, glare evaluation, and energy use for heating, cooling and lighting were compared for two locations with different climatic characteristics and latitudes. Employing proper automated shading control strategies can reduce total energy consumption and at the same time provide useful daylight without creating comfort problems. For other orientations except for south, different shading control strategies need to be followed, since solar radiation and daylight characteristics are different and discomfort problems might occur without direct sunlight. Also, different climatic zones and latitudes need to be studied separately, since the effects of façade controls will vary significantly. A detailed analysis is required for every case to investigate the balance between daylight benefits, solar heat gains and energy use (including lighting internal heat gains) while considering visual and thermal comfort. The type and properties of fenestration (e.g., glazing and shading properties) need to be considered in this analysis. Future work includes development of a systematic procedure for optimizing shading control set points for different strategies.

ACKNOWLEDGEMENT

The authors would like to thank the US Department of Energy for supporting this work through the Energy Efficient Buildings Hub. Thanks also to Hui Shen for providing experimental results.

REFERENCES

ASHRAE (2009). 2009 ASHRAE handbook fundamentals. Atlanta, GA., ASHRAE.

Chan Y-C., Tzempelikos A. (2012). "A hybrid ray-tracing and radiosity method for calculating radiation transport and illuminance distribution in spaces with venetian blinds". Solar Energy **86** (11): 3109-3124.

Correia da Silva, P., V. Leal, et al. (2012). "Influence of shading control patterns on the energy assessment of office spaces." Energy And Buildings **50**(0): 35-48.

Einhorn, H. D. (1969). "A new method for the assessment of discomfort glare." Lighting Research and Technology **1**(4): 235-247.

EnergyPlus (2007). EnergyPlus Engineering Reference—The Reference for EnergyPlus Calculations, Lawrence Berkeley National Laboratory (LBNL).

Hviid, C. A., T. R. Nielsen, et al. (2008). "Simple tool to evaluate the impact of daylight on building energy consumption." Solar Energy **82**(9): 787-798.

IES (1984). IES Lighting Handbook. Illuminating Engineering Society of North America.

ISO (2003). ISO 15099:2003(E). Thermal performance of windows, doors and shading devices - Detailed calculations. Geneva, Switzerland, International Organization for Standardization.

Iwata, T., K.-I. Kimura, et al. (1990). "Discomfort caused by wide-source glare." Energy And Buildings **15**(3–4): 391-398.

Kim, K., B. S. Kim, et al. (2007). "Analysis of design approaches to improve the comfort level of a small glazed-envelope building during summer." Solar Energy **81**(1): 39-51.

Nicol, J. F. and M. A. Humphreys (2002). "Adaptive thermal comfort and sustainable thermal standards for buildings." Energy and Buildings **34**(6): 563-572.

Nabil, A., Mardaljevic, J. (2006). "Useful daylight illuminances: a replacement for daylight factors". Energy and Buildings **38**: 905–913.

Nabil, A., Mardaljevic, J. (2005). "Useful daylight illuminances: a new paradigm for assessing daylight in buildings". Lighting Research and Technology **37** (1): 41–57.

O'Brien, W., K. Kapsis, et al. (2013). "Manually-operated window shade patterns in office buildings: A critical review." Building and Environment **60**(0): 319-338.

Orosa, J. A. and A. C. Oliveira (2011). "A new thermal comfort approach comparing adaptive and PMV models." Renewable Energy **36**(3): 951-956.

Osterhaus, W. K. E. (2005). "Discomfort glare assessment and prevention for daylight applications in office environments." Solar Energy **79**(2): 140-158.

Perez, R., R. Seals, et al. (1987). "A new simplified version of the perez diffuse irradiance model for tilted surfaces." Solar Energy **39**(3): 221-231.

Selkowitz, S. and E. S. Lee (1998). Advanced fenestration systems for improved daylight performance.

Shen, H. and A. Tzempelikos (2012). "Daylighting and energy analysis of private offices with automated interior roller shades." Solar Energy **86**(2): 681-704.

Tzempelikos, A. and A. K. Athienitis (2007). "The impact of shading design and control on building cooling and lighting demand." Solar Energy **81**(3): 369-382.

Tzempelikos A., Shen H. (2013). "Comparative control strategies for roller shades with respect to daylighting and energy performance", Building and Environment, under review.

Wankanapon, P. and R. G. Mistrick (2011). "Roller Shades and Automatic Lighting Control with Solar Radiation Control Strategies." BUILT **1**((1)).

Wienold, J. and J. Christoffersen (2006). "Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras." Energy And Buildings **38**(7): 743-757.

Yao, R., B. Li, et al. (2009). "A theoretical adaptive model of thermal comfort – Adaptive Predicted Mean Vote (aPMV)." Building and Environment **44**(10): 2089-2096.

Zhang, R. and K. P. Lam (2010). Comparison of building load performance between first principle based shading algorithm and implementable shading control algorithm. the 4th SimBuild Conference. New York, NY, USA.