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A global method for efficient synchronized shading control using the "effective daylight" concept

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ABSTRACT

The majority of modern office buildings have large glass facades on every orientation. The significant impact of glass facades and dynamic controls on energy use for lighting and air-conditioning should be carefully investigated to determine ways of saving energy while maintaining comfortable conditions for the occupants. Interior roller shades are commonly used to control glare and solar heat gain. Reduced outdoor view, glare problems, increased energy use or insufficient daylight provision are some of the problems encountered with simple shading controls. Automated control of roller shades may result in improved conditions and reduced energy use if advanced criteria are used, but recent studies have shown that appropriate set points are not easy to calculate and apply in practice. This paper extends previous findings and presents the development of a new, improved control strategy applicable for any climate and orientation. The new control method, based on the "effective daylight" transmitted into the space, aims to maximize daylight utilization while satisfying visual comfort restrictions using only one sensor mounted on the window. It can be applied to spaces with one or multiple exterior facades equipped with roller shades. The method was implemented in full-scale offices and experimental results are presented in terms of daylighting and visual comfort performance. Furthermore, the new strategy was implemented in an integrated thermal and daylighting model, validated by experimental data, to investigate the annual energy and daylighting performance of perimeter spaces with one or multiple exterior facades, and compare the new control strategy with more conventional shading controls. Overall, this study presents the principle of synchronized control of multiple shading devices on different facades (orientations) of commercial buildings. Integrated with efficient lighting and HVAC controls, it can lead to significant improvement of indoor conditions and reduced energy use.

1. INTRODUCTION

The majority of modern office buildings have large glass facades on every orientation. The significant impact of the glass facades and dynamic controls on energy use for lighting and air-conditioning should be carefully investigated to determine ways of saving energy while maintaining comfortable conditions for the occupants working in perimeter zones. Previous studies have shown energy savings potential by improving shading device properties or by employing shading control strategies (Moeseke et al., 2007, Nielsen et al., 2011, Shen and Tzempelikos, 2012). In most of the existing literature, automated shading positions (for roller shades) are limited to fully on and fully off conditions. Recently, Tzempelikos and Shen (2013) studied shading control methods that allow shades to move to intermediate positions, to prevent direct sunlight from falling on the work plane surface. The objective is to maximize utilization of solar energy and minimize energy consumption. Their study showed significant energy savings in space total source energy consumption for Philadelphia – a location with mixed weather condition. However, the method tends to result in high work plane illuminances (>2000 lux) for a noticeable portion of annual working hours which indicates that glare problems might occur.

For private office spaces with only one exterior façade with window(s), no interactions between windows need to be considered when determining the properties and control parameters (set-points) of shading devices in terms of energy and comfort considerations. This is the common case for perimeter private offices, and it has been studied thoroughly.

Nevertheless, there are also a lot of spaces with more than one window (e.g., located in the corners of a floor) in medium/large size office buildings. For such spaces, the same type of shading with the same properties and control strategies (if available) are traditionally installed. However, due to the different amounts (and characteristics) of solar radiation and natural light on different orientations, it is reasonable to study the implementation of variable properties and controls on each side of the building. Studies in such spaces are quite limited although the problem becomes more complex.

In this paper, the previously developed shading control method described in Tzempelikos and Shen (2013) is firstly improved in terms of solar protection and daylight provision. The improved strategy is examined in full-scale test rooms under real sky conditions in terms of work plane illuminance and daylight glare probability control. Experimental data is also used to validate an integrated transient thermal and lighting simulation model (Shen and Tzempelikos, 2012) which will be used for year-round study. Then, shading control strategies for spaces with more than one window are discussed. Results are presented for heating dominated, cooling dominated and mixed climates, including energy consumption and daylighting metrics information.

2. DESCRIPTION OF THE ADVANCED SHADING CONTROL STRATEGY

The advanced shading control was developed to improve daylight availability without causing glare for the occupants. Shades do not need to operate in an open/closed mode in order to achieve this objective; on the contrary, they can move to intermediate positions that depend on solar position, sky conditions and solar penetration depth relative to the occupant position. Here we refer to an improved method to protect the occupant area from direct sunlight, while adjusting the roller shade height in order to prevent high illuminances at all times and maximize daylight provision under cloudy sky conditions (Shen and Tzempelikos, 2013, 2013a).

The process involves two steps. The first consideration is to prevent direct sunlight (if present) from falling on the work plane area close to the occupant at all times. This can be easily achieved with continuous movement (proportional control) of shades to intermediate positions depending on orientation and position of the occupant (or working area) relative to the façade. As shown in Fig. 1, if the occupant (working area) is at a distance D from the façade, then the shade opening height at any given time can be calculated from:

$$h_{sh} = D \cdot tan(\Omega) \quad (1)$$

where: h_{sh} is the height of the open shade (bottom side) with respect to the work plane area and Ω is the solar profile angle (function of solar altitude α and surface solar azimuth γ: $tan(\Omega) = tan(\alpha)/cos(\gamma)$. Using this simple method, during cloudy or low illuminance conditions the shades can be fully open (She and Tzempelikos, 2013).

Figure 1: Graph showing shading position to prevent direct sunlight falling on the work plane area close to the occupant at all times

This approach takes into consideration specific space conditions including window size, façade orientation, glazing and shading properties. Its limitation has to do with high illuminance values on the work plane due to: (i) sunlight entering through the unshaded (bottom) part of the window – even though it is not directly incident on the work plane (ii) completely open shades during cloudy but relatively bright conditions or (iii) open shades during summer, when the sun is high in the sky and sunlight is not falling on the work plane but significant amounts of light enter the space. Any of these situations is probably to cause glare, when the amount of transmitted daylight is high. Associated with this issue is another problem related to high amounts of solar radiation entering into space and increasing cooling requirements, which will be significant for cooling-dominated climates.

A second consideration is therefore included, to reduce the risk of high illuminances when necessary. This can be based on either a glare index criterion or a work plane illuminance threshold. Nabil and Mardaljevic (2006) suggested that work plane illuminance values are usually preferred to be below 2000 lux to avoid visual discomfort. Thus, an extra criterion is used first to maintain work plane illuminance below 2000 lux. Considering that, employing illuminance sensors on the task area is not practical, the approach followed here is to use a sensor on the window (measuring transmitted light) and develop appropriate correlations between transmitted illuminance and work plane illuminance.

This was achieved with the "effective illuminance" control concept, where the overall transmitted illuminance (through shaded and unshaded portions of the window) in Eq. (2) is plotted against work plane illuminance at target (occupant) points on the work plane throughout the year. The shades are controlled so as to prevent sunlight from reaching the work plane. Simulation can be used for that process, using TMY3 data with the Perez et al. model (1990) and an interior luminous flux processing approach such as the radiosity method, ray-tracing method or a mix of ray-tracing and radiosity solutions (Chan and Tzempelikos, 2012). Using these correlations, we can establish a threshold (upper limit, E_{esp}) for E_{eff}, above which work plane illuminances would be unacceptable (shades will not move to open further) and set a constraint in shading control to avoid high illuminances and risk of glare.

The effective illuminance through the window(s) is defined as:

$$E_{eff} = \frac{\sum_i (E_{gi} \times A_{gi} + E_{shi} \times A_{shi})}{\sum_i (A_{gi} + A_{shi})} \tag{2}$$

where E_g and E_{sh} are the illuminance transmitted through the unshaded and shaded window parts of the i^{th} window in the studied space respectively, lux; A_g and A_{sh} are the areas of the unshaded and shaded window parts, m^2. With the determined threshold (E_{esp}) for effective illuminance through the window(s) (E_{eff}), the shade position h_{sh} (portion of unshaded window) is then obtained by Eq. (3) for spaces with only one exterior façade (assuming all windows on the same façade have the same height and use the same shading control strategy).

$$E_{sh} \cdot (H - h_{sh}) + E_g \cdot h_{sh} = E_{esp} \cdot H \tag{3}$$

where H is the entire window height. When applied to spaces with multiple exterior facades (windows facing different orientations), the determined threshold of effective illuminance that enters the space through windows cannot be used to obtain a shade position directly, but is used to calculate a specific illuminance threshold for each window in the space (Eq. (4)). Then the shade position for each window can be determined according its own threshold and window height using Eq. (3).

$$E_{espi} = \frac{E_{esp}}{E_{eff}} \cdot E_{effi} \tag{4}$$

The final shade position is decided as the minimum of the two considerations from Eq. (1) and Eq. (3), to ensure protection from high illuminances while allowing the maximum possible amount of daylight without direct sunlight on the work plane area:

$$h_{sh} = \min\left\{D \cdot tan\Omega\ , \frac{(E_{esp} - E_{sh}) \cdot H}{E_g - E_{sh}}\right\} \tag{5}$$

Therefore, the developed algorithm selects the position of the shade at any time based on room and solar geometry, glazing and shading properties, and window size and positioning, using only one sensor on the window.

3. FULL-SCALE EXPERIMENTAL EXAMINATION, IMPLEMENTATION AND VERIFICATION OF CONTROL ALGORITHM PERFORMANCE

3.1 Experimental facilities

The developed advanced shading control strategy was implemented in full scale test facilities to examine its effectiveness in terms of daylighting and thermal performance. The facility is located in Purdue University, in West Lafayette, Indiana. It consists of two side by side test offices with reconfigurable facades. The two test offices are insulated (R-20 plus construction materials) and airtight (air and vapor barrier all around the perimeter) with a concrete floor sitting on a steel frame and a false ceiling (0.6m high plenum space) that can be used for ducting and lighting circuits. The dimensions of the test rooms are 5m wide by 5.2m deep by 3.4m high with a glass façade facing south. The window has a height of 2.1m, starting from 0.6m above floor and extending to the entire façade width, and consists of aluminum curtain wall framing and glass. A detailed description about the experimental facility can be found in Shen, Chan and Tzempelikos (2013). The measurements presented in this section were performed from June-2013 until April 2014 and they are part of long-term measurements conducted during several months. The angular glazing and shading properties are shown in Fig. 2 and Fig. 3. Roller shades have direct-direct and direct-diffuse transmission characteristics (Kotey et al., 2009) which were measured with an integrated sphere. The installed roller shades have a high reflectance (77%) on the exterior side and a low interior reflectance (5%), with 4% openness. During the experiments, shades were controlled with the advanced shading control strategy during daytime (8am~6pm) and were closed during other times.

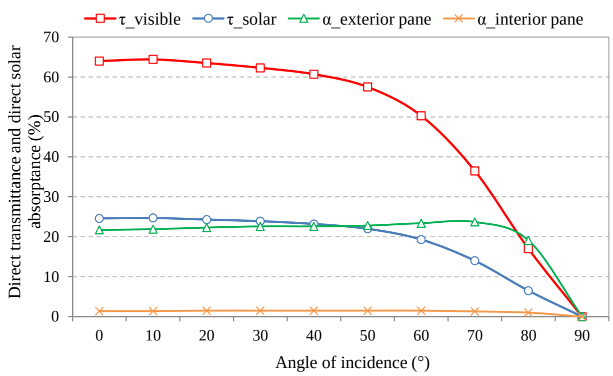


Figure 2: Glazing angular properties: visible and solar beam transmittance, exterior and interior pane absorptance

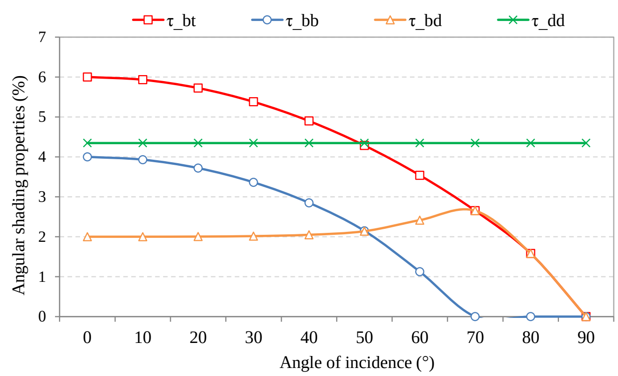


Figure 3: Angular properties of the tested roller shades: τ_bt is beam-total transmittance, τ_bb is beam-beam transmittance, τ_bd is beam-diffuse transmittance and τ_dd is diffuse-diffuse transmittance

3.2 Correlations to establish effective illuminance threshold

Incident, transmitted and work plane illuminances were recorded every minute for an extended period of time (covering the entire year). For the test office configuration described above, the work plane illuminance (measured near the façade and at the back of the room) is plotted against the effective illuminance transmitted through window to determine a threshold for effective illuminance (Fig. 4). At this stage, the shades are controlled to prevent direct sunlight falling on work plane surface.

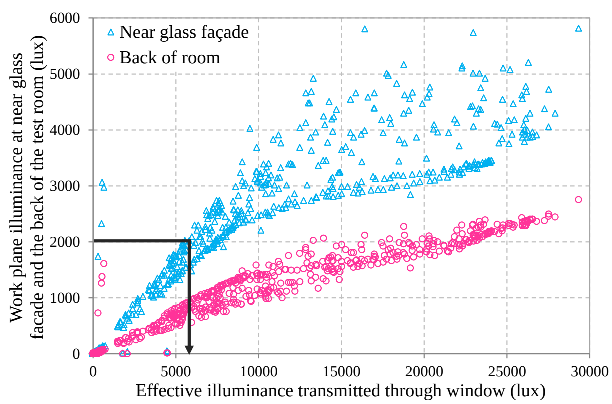


Figure 4: Correlation between "effective" transmitted illuminance and work plane illuminance to determine threshold E_{esp} for selecting shade intermediate positions.

As can be seen from Fig. 4, when the effective illuminance through window reaches about 6000 lux, the work plane illuminance near the façade reaches 2000 lux. Therefore, 6000 lux was determined as the transmitted illuminance threshold for this space to use the advanced shading control. Fig. 4 also illustrates that this threshold allows enough daylight to enter the space, maintaining the work plane illuminance at the back of the room above the recommend value of 500 lux for offices. For larger spaces, this last condition might not be satisfied.

The effective illuminance control strategy was applied with the new threshold in the test offices to validate its effectiveness. Representative results for six days in September are shown in Fig. 5. The work plane illuminance values at all positions were well between 500 lux to 2000 lux for almost all of the time (Fig. 5) –therefore this control strategy is able to control illuminance values between specified limits without having to close shades completely. Shading operation can be also expressed as the unshaded window fraction (unobstructed outside view) which is also illustrated in Fig. 6. Since the office is facing south, the shades have to close more around noon, and they can be more open during morning and afternoon without causing problems of excessive illuminance.

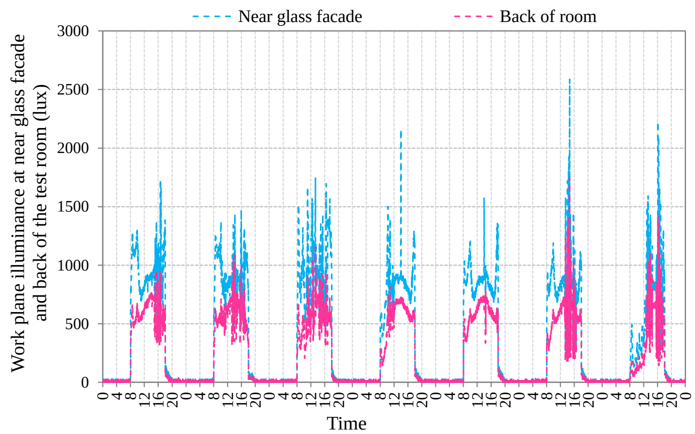


Figure 5: Measured work plane illuminance near the glass façade and in the back of the room

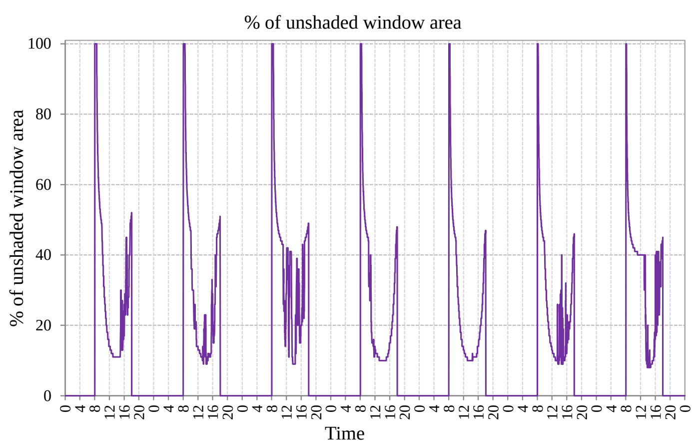


Figure 6: Variation of shades height (bottom side) during the experiment period

As mentioned before, the developed strategy is supposed to improve daylighting conditions in the summer, when the sun is high in the sky, but high amounts of daylight are incident on the façade. To demonstrate this, measurements with controlled shades were collected during several summer and shoulder season months, with a large amount of data to support longer-term findings. To include the vast amount of data collected, the measured incident illuminance on the façade is divided into 100 intervals (from 0 lux to 100 klux, 1000 lux increments). Then the measured work plane illuminances (close to the façade and in the back of the office) are plotted against incident illuminance in each interval showing the maximum, upper quartile, median, lower quartile and minimum values (Fig. 7). This statistical analysis reveals useful information for (i) the variation of work plane illuminance as a function of exterior incident illuminance and (ii) the general distribution of work plane illuminance within a range of exterior incident illuminance (e.g., within each interval but with different solar position or sky conditions).

Work plane illuminances near the façade exceeded the recommended limit of 2000 lux at certain instances when the incident daylight on the façade is between 8 to 18 klux. However, for brighter conditions, indoor illuminances were well maintained between 500 lux and 2000 lux. This can be attributed to the selected lower threshold (6000 lux transmitted through glass) for opening shades completely when the sky is dark or other uncertainties during experiments (e.g. time delay between shade position adjustment and measurement). This problem can be solved by adjusting the threshold to a slightly lower value. Nevertheless, the overall performance is quite good and the exceeded values are not prohibitive (see glare analysis below), so the lower limit was kept for reducing frequent shading operation and allowing more daylight. Also, the daylighting conditions in the back of the room are quite satisfactory.

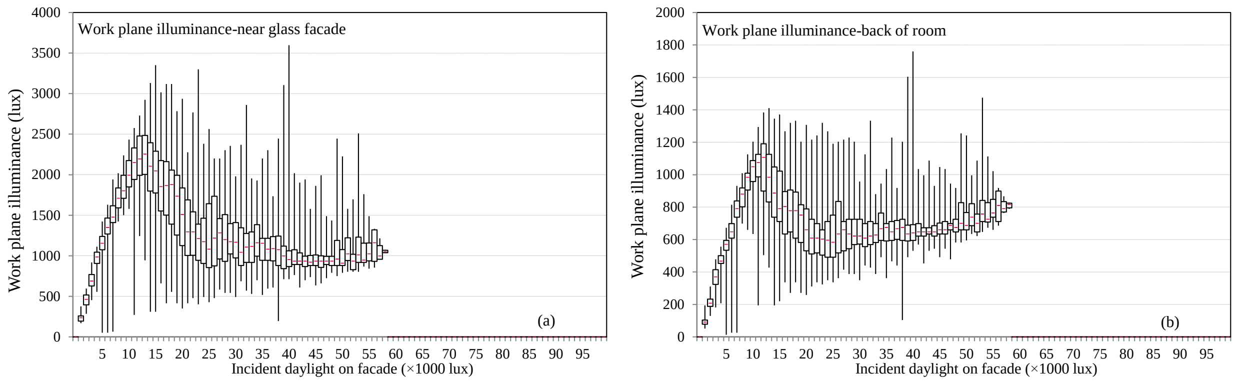
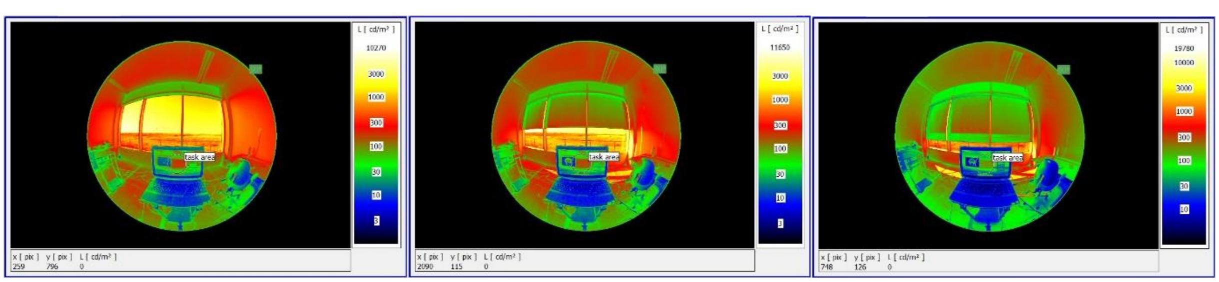


Figure 7: Variation of measured work plane illuminance near the glass façade (a) and in the back of the room (b) as a function of incident daylight on façade, as well as box plot for each incident daylight interval showing maximum, upper quartile, median, lower quartile and minimum values of work plane illuminance

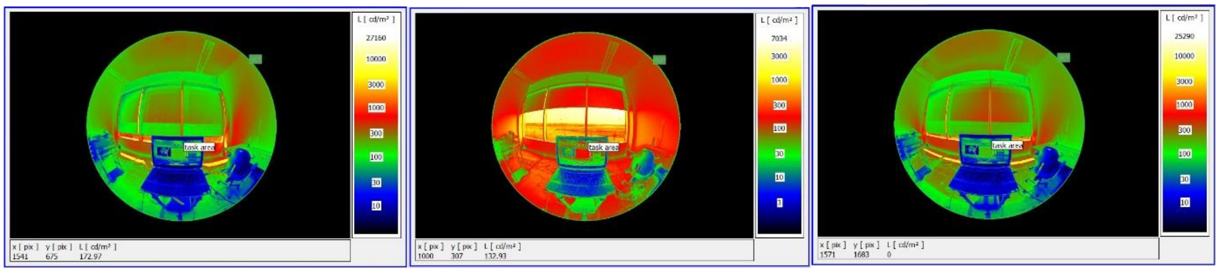
To further examine the developed shading control strategy in terms of visual comfort, a HDR camera with a fish-eye lens was used to monitor the luminance field and estimate occupant daylight glare probability (DGP). The camera was placed on a 1.1m high tripod (stands 2m away from the glass facade) and facing the windows. A photometer was also placed on the camera to measure the vertical (eye) illuminance for checking results. The measured vertical illuminance was used to calculate the simplified daylight glare probability (DGPs) (Wienold, 2006, 2007) which was compared with standard DGP to evaluate differences and investigate if DGPs can be used as an easier and faster glare indicator.

Figure 8 shows hourly snapshots of the monitored luminance mapping with the camera and calculated DGP values for several hours during a representative day. Image processing and DGP calculation were conducted using the Labsoft software that uses the evalglare method (Wienold, 2007). Glare probability does not exceed 35%, which is considered as "perceptible" glare. A comparison between DGP and DGPs for the same day of measurements is shown in Fig. 9. The two indices are generally in good agreement, with DGP being a bit higher due to the contrast term that is present since there is sunlight coming through the bottom part of the window. The average maximum absolute error during office hours (8am~6pm) is 13.8% and the root mean square difference between them is 0.023. This comparison indicates that we can use DGPs for faster annual evaluation of visual discomfort using this type of shading control.

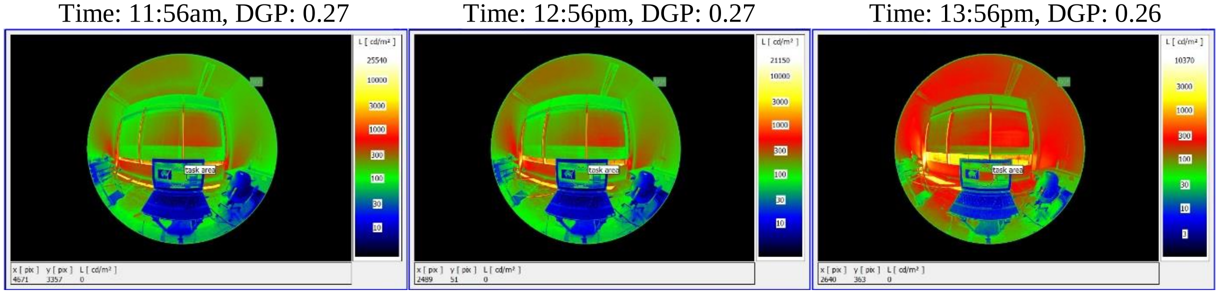
Simplified daylight glare probability, obtained from measured vertical illuminance, is plotted in Fig. 10 as a function of transmitted effective illuminance, together with work plane illuminance values. DGPs remains below 35% for almost all of the time, while work plane illuminance is maintained within the desired range, with few exceptions closer to the windows -that are not expected to cause glare. This means that work plane illuminance can probably be allowed to exceed 2000 lux at certain instances, up to 2500 lux. Note that the values shown in Fig. 10 are the maximum measured values among 4 work plane illuminance sensors to ensure strict consideration of illuminance fluctuations in the space.



Time: 8:56am, DGP: 0.33 Time: 9:56am, DGP: 0.30 Time: 10:56am, DGP: 0.26



Time: 11:56am, DGP: 0.27 Time: 12:56pm, DGP: 0.27 Time: 13:56pm, DGP: 0.26



Time: 14:56pm, DGP: 0.27 Time: 15:56pm, DGP: 0.26 Time: 16:56pm, DGP: 0.25

Figure 8: Snapshots of monitored luminance mapping and obtained DGP values during a representative day in April

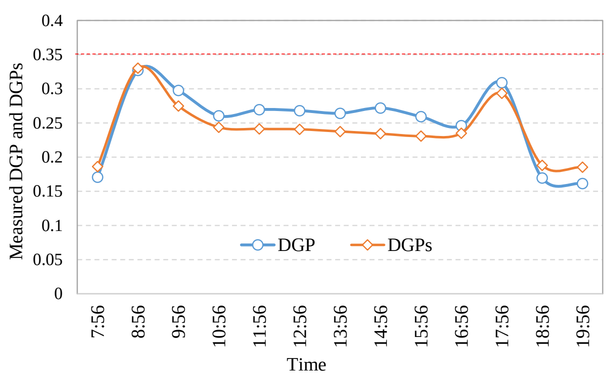


Figure 9: Variation and comparison between DGP and DGPs for April 1 2014

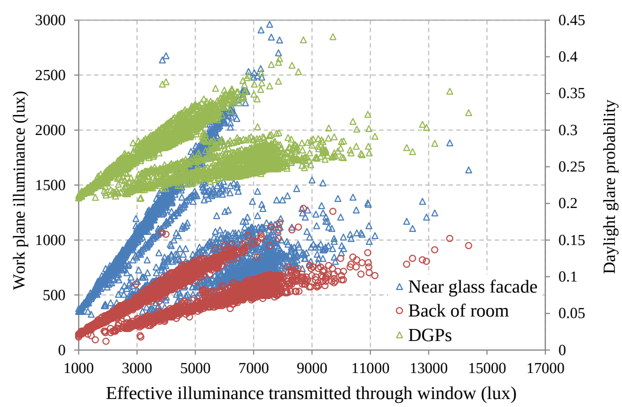


Figure 10: Variation of measured work plane illuminance and DGPs during working hours (8am ~ 6pm) during measurements with controlled shades (May and April)

4. IMPLEMENTATION OF THE DEVELOPED CONTROL ALGORITHM IN BUILDING SIMULATION AND MODEL VALIDATION WITH FULL-SCALE EXPERIMENTS

For complete annual analysis at different locations, creditable simulation is always the most efficient approach. The integrated thermal and daylighting model developed in previous studies (Shen and Tzempelikos, 2012, 2013b) has been previously validated by comparing with EnergyPlus for simplified shading control cases (Shen and Tzempelikos, 2014) and with experiments using different shading control strategies (Shen and Tzempelikos, 2013). Further improvements in the current version include discretization in more surfaces, consideration of comparative directionality of sky light and ground reflected light transmitted into space through windows, and utilization of shading properties. To validate the simulation model with the embedded effective illuminance control, comparison of model results with experimental measurements was performed. Fig. 11 compares the measured and simulated work plane illuminance values near and away from the façade for a representative week of measurements, with weather conditions shown in Fig. 12. A good agreement is observed with some deviations due to separation of diffuse daylight components entering the space based on the Perez et al. model. A detailed variation of measured and modeled work plane illuminances near the façade is shown in Fig. 13.

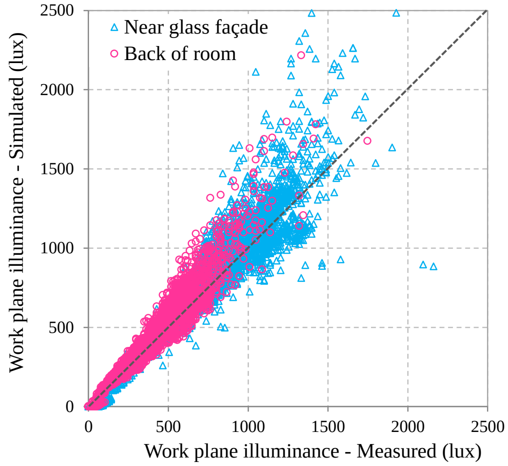


Figure 11: Comparison of measured and work plane illuminance near and away from the façade

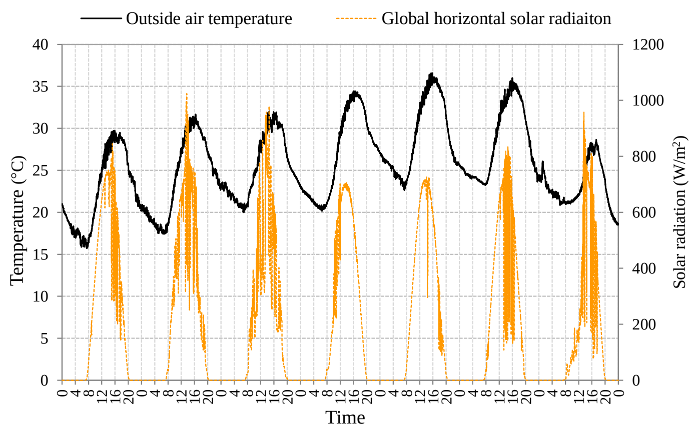
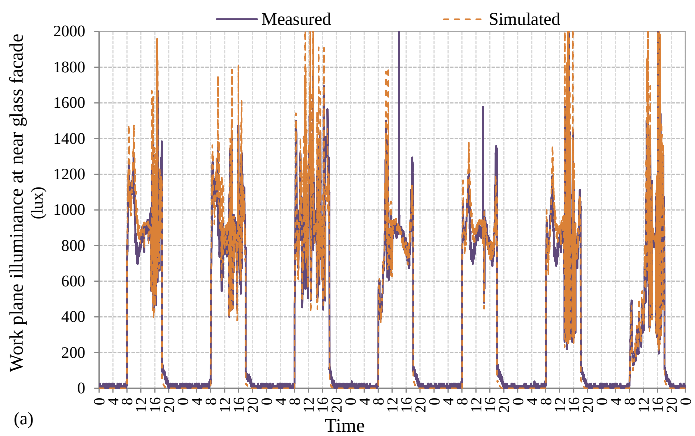


Figure 12: Measured outside air temperature and global horizontal solar radiation levels during a representative measurement week



(a)

Figure 13: Detailed work plane illuminance variation near the façade

5. ANNUAL EVALUATION OF THE DEVELOPED CONTROL METHOD

The new shading control strategy was developed based on a previous control method with intermediate shade positions (protecting work area from direct sunlight), to solve the issues of high work plane illuminance and excessive solar radiation entering into space. In this section, the two shading control methods are compared for three different climates: Chicago (heating), Los Angeles (cooling) and Philadelphia (mixed) with results include energy consumption and daylighting metrics.

The comparison is first performed for a perimeter office space with only one exterior façade with window(s) (intermediate floor) - the other room surfaces are in contact with conditioned interior spaces that have the same indoor air temperature as the studied space (heat storage in these surfaces and the convection heat transfer between them and air are still considered). The space dimensions are 4 m wide by 4 m deep by 3 m high. It has typical masonry (brick) wall and a window accounting for 40% of the total exterior façade area (3m wide by 1.6m high, starts from 0.8m above floor). Total thermal resistance of the opaque section of exterior façade is 3.5 m^2K/W. The same type of glazing and roller shades as described in the experimental section are used. The space is occupied from 8:00 am to 6:00 pm. Occupant density in the space is assumed to be 0.11 p/m^2 with sensible heat of 76W/person. The lighting system is continuously dimmable with an installed power density of 10 W/m^2 at full power. Load factor for other internal equipment is assumed as 5.4 W/m^2. Air conditioning is operating throughout the whole year, with variable temperature set points for office time (heating: 22 ºC, cooling: 24 ºC) and non-office time (heating: 18 ºC, cooling: 26.6 ºC). In this study, it is assumed that heating consumes natural gas (efficiency is 0.8) and cooling consumes electricity (COP is 3.5). The convert factors for natural gas and electricity to source energy are 1.047 and 3.34 respectively. A grid with dimensions of 1m ×1m is used for work plane illuminance calculation; the working area is 0.5m from all vertical surfaces and work plane surface is 0.8m above floor.

The threshold of the effective illuminance can be generalized for the same space condition, independent of the weather condition, space orientation, glazing and shading properties. Therefore, the same threshold value of 5000 lux can be used for all the studied locations to maintain work plane illuminance between 500 lux and 2000 lux.

Table 1: Comparison between original and improved shading control: continuous daylight autonomy (DAcon), time-area percentage of working time when shades are partially unshaded (UWta), time ratio of annual working hours when work plane illuminance at least at one position exceeds 2000 lux (Ewp > 2000 lux) and DGPs

Location	**Orientation**	**South**		**East**		**North**		**West**	
		SC-Original	SC-Improved	SC-Original	SC-Improved	SC-Original	SC-Improved	SC-Original	SC-Improved
Philadelphia	DAcon (%)	86.5	78.7	89.3	83.7	90.3	87.3	87.2	81.8
	UWta (%)	66.6	42.0	87.4	64.6	98.7	77.7	71.8	51.2
	E_{wp}>2000lux (% of working hours)	48	1.3	40	0.2	31.2	0	36.8	1.7
	DGPs (%)	27.1	0	15.6	0	10.3	0	16.1	0
Chicago	DAcon (%)	85.1	77.9	88.1	83.2	88.9	85.9	86.1	81.1
	UWta (%)	68.6	42.4	88.6	64.6	98.5	75.9	73.8	51.0
	E_{wp}>2000lux (% of working hours)	48.5	3	40.9	0.3	34.2	0	40.3	2.7
	DGPs (%)	29.2	0	16.3	0	11	0	18.5	0
Los Angeles	DAcon (%)	88.7	78.9	91.5	84.6	91.7	87.4	89.5	82
	UWta (%)	66.5	37.5	86.9	59.5	97.3	71.7	67.4	42.7
	E_{wp}>2000lux (% of working hours)	54.6	1.04	39.8	0.4	31.8	0	41.8	1.3
	DGPs (%)	30	0	16.9	0	10.6	0	18.6	0

Table 1 compares the shading operation and daylight performance between the original and improved shading control strategy for all four main orientations in the three locations. The two shading controls result in similar daylight performance for all orientations and locations. However, shading operation is quite different. The improved method achieved almost the same continuous daylight autonomy values (DAcon) with much lower time-area fractions of unshaded window (UWta). This reduction, in consequence, greatly improved the performance of the control strategy in maintaining work plane illuminance below the recommend limit (2000 lux) and reducing DGP. From Table 1, we can also see that the difference in time-area fractions of unshaded window is higher in Los Angeles than in Philadelphia and Chicago although the values and differences in continuous daylight autonomy in each orientation are quite similar. This is because the geographical location and solar radiation levels in Los Angeles are quite different. Another point worth noticing is that the difference in time-area fractions of unshaded window does not equal to the time fraction of direct viewing of outside. Time-area fractions of unshaded window is the time averaged unshaded window area percentage –therefore, at the same time step, the improved control results in lower unshaded window area than the original strategy, but the occupants still have a direct outside view. Similar results are observed for spaces with multiple windows on different facades.

6. CONCLUSIONS

This paper presents the development of a new, improved shading control strategy based on the 'effective illuminance' concept. The method is an extension of previous findings aiming to solve the problem of high work plane illuminances that may cause visual discomfort, as well as to maximize daylight utilization. The new algorithm was implemented in full-scale test offices and experimental measurements proved its effectiveness in controlling work plane illuminance within the recommended range. The experimental results were also used to validate a daylighting and thermal model developed for annual investigation of the control performance for different orientations and three different locations. The principles of the shading control strategy lead to generalized threshold for effective illuminance for the same space condition (room size, surface reflectance), independent weather conditions, space orientation, glazing and shading properties. This gives the opportunity for establishing a guideline of using the control in categorized spaces. Compared to previous shading control methods, the new method maintains high daylight autonomy values while reducing excessive illuminance and glare probability.

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