THE POTENTIAL OF COMFORT DAYLIGHTING DESIGN ON IMPROVING THE ENERGY EFFICIENCY OF COMMERCIAL BUILDINGS

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ABSTRACT

This paper explores means for more effectively exploiting daylight in buildings through extending periods of illumination free of glare problems. The key concept is to quantify and examine the impact of selected design parameters, e.g. light shelves, on the admission of daylight within buildings. The University of Calgary's Information and Communication Technology (*ICT*) office building is used as a base model, whereas innovative techniques are developed and presented in this study. Results show that there is still a potential to improve the daylighting design of the building and hence reducing the electric energy consumption.

INTRODUCTION

A key, but often neglected, aspect of daylight harvesting is the control of glare from direct sunlight, especially when using sidelighting at northerly latitudes (above 45^o). To date, two widely used devices for glare control are venetian blinds and light shelves. Most difficulties experienced with automatic blinds are due to frequent blind operation and poor coordination between lighting and blind controls. In the case of manual blinds, occupant's behaviour has been shown to limit daylight admission. If the blinds were closed due to the increasing outside glare or solar radiation, they seldom were opened again and electric lighting would be used (Bordass et al. 1994; Reinhart et al. 2002). Venetian blinds reduce the daylight admission even when open; the transmission of diffuse daylight through conventional, fully opened venetian blind slats (horizontal angle) is as low as 50% of the total incident daylight (Kischkoweit-Lopin, 1998). On the other hand, sun penetration is a problem with light shelves and other horizontal shading devices, especially in winter. The result is that daylight harvesting to improve energy performance is impaired by measures to control glare from sunlight.

Important limitations for exploiting recent innovative systems, such as light-duct systems (Courret et al. 1998) to collect and transport daylighting are the high initial and operating costs; glare problems; and uneven distribution of daylight (IEA, 2000). Many advanced systems, such as some automatic blind systems that cannot be retracted, permanently obstruct the view. Therefore some researchers (IEA, 2000) recommend using a separate daylighting aperture.

This paper presents the search for improving the energy performance of high latitude buildings by using *RADIANCE* simulations to assess the performance of selected design features of a prototype building located in Calgary, Canada to further advance daylighting techniques and to develop innovative means of glare control.

Description of the Base Model

The Information and Communication Technology (*ICT*) is a rectangular office building, completed in 2001 at the University of Calgary. It consists of seven floors with a total built-up area of about 17,000 m^2. The building includes student spaces, corridors, and laboratories in the core and modular office spaces and service risers at the perimeter. Most of the offices face east and west.

A typical private office (4.5 m by 2.9 m) is used as a base model. Each office includes an L-shape desk with computer, filing cabinet, and whiteboard on a sidewall. The window is divided into two parts, lower with venetian blinds and upper without. A radiant heating panel between these glazed areas acts as an internal light shelf. The window exposure to the sky is assumed to be unobstructed.

Figures 1-3 show the plan, section and elevation of the base office. "Camera" in Figure 1 refers to the *RADIANCE* viewing position. The reference point was located in front of the computer screen to reflect the most critical position on the working plane.

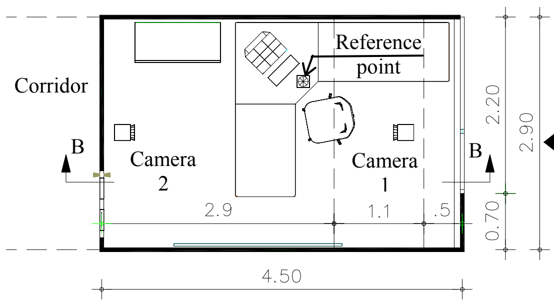


Figure 1. Office plan

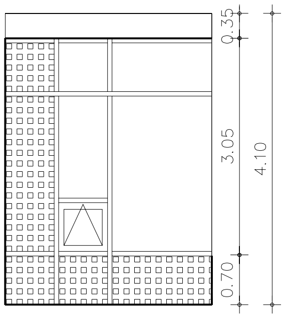


Figure 2. Front view A

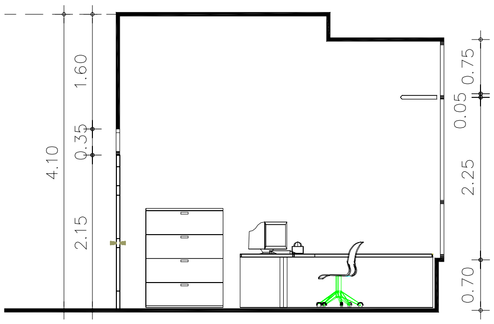


Figure 3. Section B-B

Surface reflectances of 20%, 50%, and 50% were used for floor, walls, and concrete ceiling, respectively. Window with a transmittance of 55% and reflectance of 8% using double-glazed panes with 3 mm clear laminate and 7 mm thickness was selected from the *RADIANCE* library. Simulations were focused on clear sky with sun to scrutinize extreme glare conditions resulting from penetration of direct sunlight. The design illuminance threshold is 500 lux (IESNA, 1993) for the reference point at 0.75 m above the ground, as shown in Figure 1.

Table 1
Reference point illuminance for the base model at the solstices and equinoxes

Time [hr]	**Illuminance of base model reference point** [lux]			
	21-Dec	**21-Mar**	**21-Jun**	**21-Sep**
	Winter	Spring	Summer	Fall
	East			
0900	1024	13169	25295	15126
1000	629	2056	1054	1701
1100	515	1011	757	803
1200	288	496	531	450
	West			
1300	261	395	478	422
1400	542	750	862	850
1500	589	1146	1046	1255
1600	770	1506	25629	1468

The simulation results (Table 1) show that glare occurs between 0900 and 1100 for the east facade and from 1400 to 1600 for the west facade. Sunny patches were also found on sidewalls at 1200 and 1300. The discrepancy of numerical results in equinoxes at 0900 and 1600 is due to the sun position relative to the space. For east faced, the sunrays mainly strike the sidewall close to the reference point and occasionally reach the reference point, e.g. in March at 0900, while they are incident on the other sidewall for the west facade.

The procedures used in this study to develop daylighting design patterns employed the followings:

- The impact of selected daylighting design alternatives relative to the base model was analyzed in terms of illumination and visual comfort;
- The evaluation is based on the analysis of calculated illuminances and simulated daylight scenes within the office; and
- The most promising design features were used to develop design guidelines.

In order to minimize the number of required simulations, analyses were limited to the solstices and equinoxes. They were also mainly limited to 0900, as this is the most critical time for the east facade in terms of glare. For this study, occupant body shadow was ignored. The venetian blinds were also eliminated from simulations to examine the impact of selected design parameters on the daylight admission without window coverings.

DESIGN PARAMETER ANALYSIS

Several design alternatives have been developed. Parameters are classified in the following categories:

Modifications of conventional shading device systems:

- internal light shelves
- external overhangs
- venetian blinds

Modifications of architectural design patterns:

- percentage of window area
- glazing visual properties
- reflectance of interior surfaces

3. Modifications of daylight-responsive control system.

Only the analysis of shading devices and architectural design are presented in this paper. Each parameter was varied individually.

Modifications of the Internal Light Shelf

To investigate the impact of the internal light shelf, the lower (main) window was treated as opaque, so daylight entered only via the upper window.

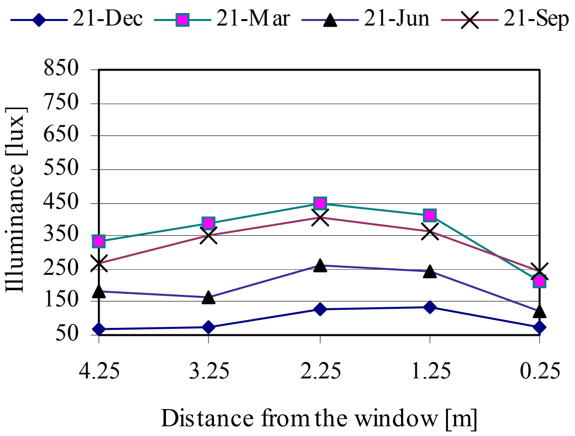


Figure 4. Center-line illuminance levels for Alt1, base model

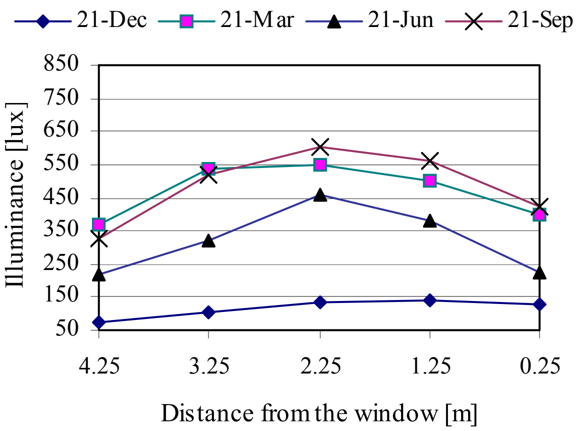


Figure 5. Center-line llluminance levels for Alt2, no light shef

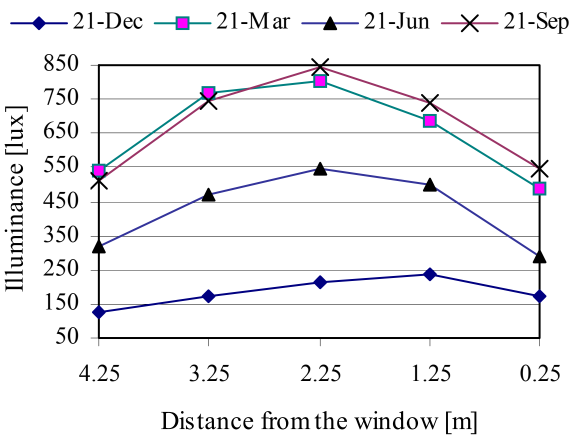


Figure 6. Center-line llluminance levels for Alt3, upper window height increased 50%

"Alt1" is the base model (with light shelf) while "Alt2" is the "no light shelf" alternative. Figures 4 and 5 provide the daylight distributions for the east facade at 0900. Illumination was calculated along the window wall centre line. Alt1 and Alt2 results show even daylight distributions, except in summer for Alt2. The illuminance levels for Alt2 are higher than that of Alt1. This indicates that the light shelf is mainly functional in summer with high altitude sun. Furthermore, the light shelf reduces the illuminance level for the entire room. For instance, the illuminance level is 400 lux at 2.25 m from the window of Alt1 in September, while it was 600 lux for Alt2, at the same point.

Figure 6 presents the impact of increasing the height of the upper window by 50% (Alt3). Increasing the height of the window led to increases of the reference point illuminance levels with respect to that of the base model (Figure 4). Furthermore, results showed a better distribution of daylight within the base model (Alt1) compared with the corresponding results of (Alt3). For instance, the maximum difference of illuminances for Alt1 is 120 lux in March, while it is 330 lux in September for Alt3.

Other simulations showed that increasing light shelf depth reduces the reference point illuminance levels. For example, doubling the depth to 1.0 m led to a reduction of 26% to 53% of illuminance levels of the reference point for the east facade from 0900 to 1200.

Assessment of Overhangs

For this parameter, the internal light shelf and upper window were removed to analyze overhangs for the lower window. Table 2 presents the reference point illuminances for east facade at 0900 on the 21st of each month. Comparing results from Tables 1 and 2 shows that the lower window is the main source of daylight within the office. The contribution of this window to the total illuminance ranged between 88% in December to 97% in June. This is due to the larger area of the lower window with respect to that of the upper window. It is clear that the lower window is the main source of glare because sun penetration is in the occupied zone.

First, a horizontal overhang was placed above the lower window, extending the width of the room. The overhang was assigned a reflectance of 70%. To determine the depth of the overhang, the following equation (Hutcheon et al., 1995) was used:

$$d = h / (\tan \beta / \cos \gamma) \qquad [1]$$

Where: 'd' is the depth of external overhang; 'h' is the height of window; 'β' is solar altitude; and 'γ' is the solar-surface azimuth, which is the sum of solar azimuth and surface azimuth.

Table 2
Reference point illuminances for the lower window of the base model

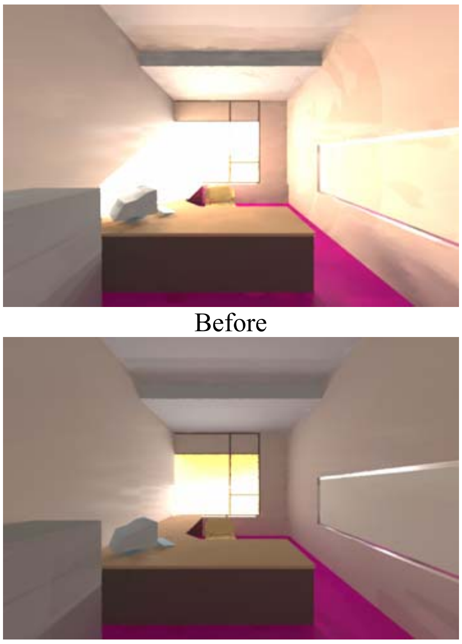
	Month			
	Jan	Feb	Mar	Apr
Illuminance [lux]	963	3991	12412	20205
	Month			
	May	Jun	Jul	Aug
Illuminance [lux]	24110	24517	23679	20113
	Month			
	Sep	Oct	Nov	Dec
Illuminance [lux]	14436	1895	934	903

The calculations were carried out for each hour 0900-1600. A depth of 1.85 m was selected for the overhang to shade the east facade from sunlight for the following periods (i) at 1200 for the entire year; (ii) at 1100 from March 15 to October 15; and (iii) at 1000 from May 15 to July 15. These results can be applied to the west facade with the corresponding time change. For example, east facade results at 1200 are approximately equivalent to west facade results at 1300. Although the depth of 1.85 m is impractical for real buildings, it was used to investigate the impact of the overhang on daylighting. Then, it was modified to achieve final recommendations.

Several alternatives to control the glare from sunlight were explored. One of the effective solutions was to slope the overhang down over the window. Tilt angles of 15°, 30°, 45°, and 60° were used. The positive sign of the angles refers to the downward direction. The detailed analysis of simulated scenes on the 21st day of each month at 0900, 1000, and 1100 for the east facade illustrates the followings:

At 0900, the tilt angle of 60° impedes sunlight from March 21 till September 21, while blinds are necessary for the other periods, especially in winter due to the lower sun angles. At 1000, the tilt angle of 60° is effective from September 22 to March 20, while inclination of 45 ° can be used from March 21 to September 21. The tilt angle of 60° is used from October 21 to March 20 at 1100 while the horizontal overhang is applied for the rest of the year. The tilted angles could be done with a moveable overhang.

Figure 7 shows the situations before and after using a tilted overhang of 45° for east facade on March 21 at 1000.



Before

After

Figure 7. The impact of using movable overhang on glare control

Modifications of the Window-to-Wall Ratio

The glazing area is considered to be the total area of the upper and lower windows, thus the proposed glazing area is 2.20 m by 3.05 m. The internal light shelf was removed. A reduction of 0.3 m of the height of the window was carried out. This reduction is equivalent to a decrease of 10% of the total window area. The height was gradually decreased, generating several alternatives for this parameter.

Figures 8, 9, and 10 present the correlation between the reductions of window area and the corresponding illuminance levels at the reference point. The measurements were conducted on the 21st of December, March, June, and September at 0900 for east facade; and 1600 for west facade.

The reduction of glazing area led to a considerable decrease of the reference point illuminance. For example, when the glazing area was decreased by 50%, there was a reduction of 33% and 47% of illuminance for east and west facades respectively.

The discrepancies in Figure 9 are due to the sunrays of the east facade striking directly the reference point, while the reflected sunrays only affect the same point for the west facade. In equinoxes, the 70% reduction of the window area of the east facade hindered the direct sunrays to reach to the reference point and thus led to a great reduction of the illuminance levels.

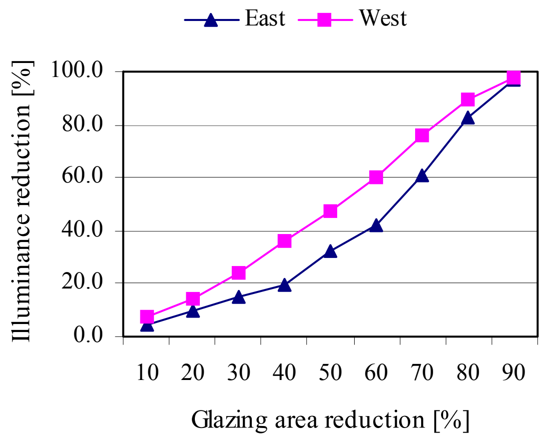


Figure 8. The impact of glazing area reduction on reference point illuminance in Dec.

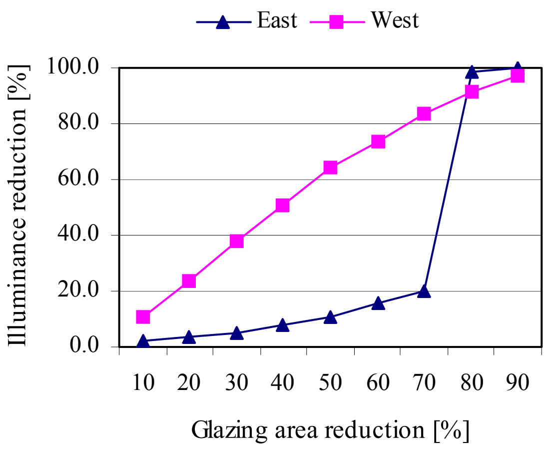


Figure 9. The impact of glazing area reduction on reference point illuminance in Mar and Sep.

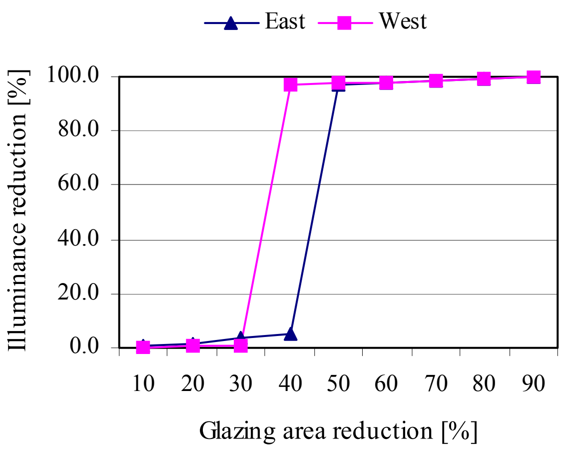


Figure 10. The impact of glazing area reduction on reference point illuminance in Jun.

Modifications of the Glazing Properties

Of glazing properties, transmittance has the greatest impact on the daylight admission, therefore it was varied while other properties were held constant at the initial value.

Figure 11 illustrates the impact of changing the transmittance values on the reference point illuminance on December 21st at 0900 and 1600 for east and west facade, respectively.

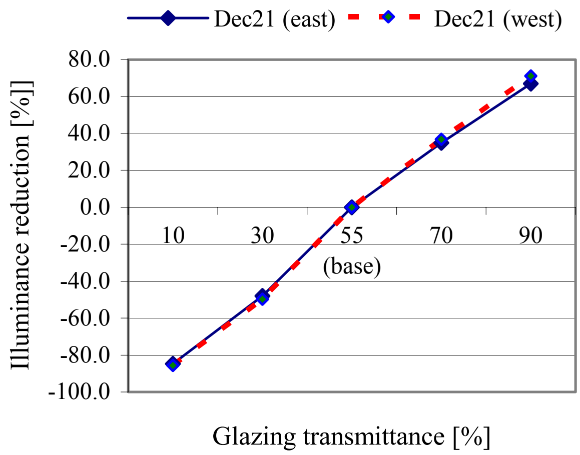


Figure 11. The impact of glazing transmittance on the reference point illuminance

Results show a linear relationship between the glazing transmittance and illuminance levels. A significant reduction of illuminance was noticed when the transmittance value was decreased. For instance, decreasing the transmittance value by 25% led to an illuminance reduction of 48%, or 433 lux and 225 lux for east and west facades, respectively. There is also a good agreement between east and west facades for this relationship. Although the glazing transmittance parameter has a major impact on illuminance levels, it is ineffective for glare control.

Recommendations for the Final Alternative

The preceding analyses provide a basis for a recommended design. The internal light shelf was removed and the glazing areas of the windows were modified. The height of the upper window was enlarged with a corresponding decrease in the height of the lower window to achieve equal heights of 1.3 m for both windows while the base model width was used. External overhangs were placed above windows to control sunlight, as shown in Figure 13. The depth of the overhang was estimated to be 1.0 m using the equation [1].

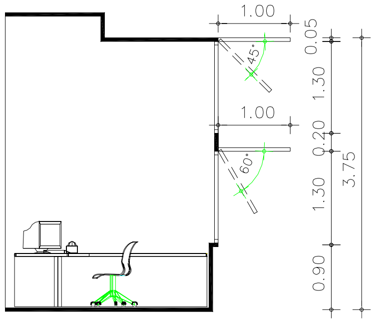


Figure 13. Section of the window wall for the final alternative

From the detailed analysis of simulated scenes, the criteria for the tilt angles of movable overhangs were established for the east facade.

Lower window sunlight control

At 0900, tilt angles of 45^o and 60^o are required from March 21 to September 21; and from September 22 to March 20, respectively. Although sun penetration was noticed close to the reference point in November and February (Figure 14), it will not affect the entire visual performance of the office. It is recommended that the L-shape desk be moved to the other side wall to avoid sunrays incident on this wall. The desk is maintained in its original position for the west facade. A tilt angle of 45^o is used at 1000 from August 22 to April 20, while it is 0^o (horizontal) from April 21 to August 21. At 1100 and 1200, horizontal overhangs are used for the entire year.

Upper window sunlight control

At 0900, tilt angles of 45^o from April 21 to August 21 and 0^o for the rest of the year are required. At 1000, 1100 and 1200 horizontal overhangs are employed. Similar guidelines are used for west facade from 1300 to 1600 with the corresponding times of east facade.

Figure 14 illustrates glare on working plane on February 21st, while Figure 15 presents the impact of using tilted overhangs on June 21st. Simulations were carried out at 0900 for east facade.

Figure 14. Glare on working plane on February 21st

Figure 15. Final alternative on June 21st at 0900

In order to exploit the daylight, the visual comfort for final alternative was examined. The unitless glare index of the Guth Visual Comfort Probability method was applied (Murry et al. 2001). This index is a measurement of the percentage of satisfied people with a particular view, whereas the Guth values of 65% and 52% represent the sedentary and transit conditions, respectively. The glare threshold factor of 7 is used for this index. Camera 1 and 2 (Figure 1) are used to create scenes from different view angles for the office.

Table 3 shows the glare index for east facade, while Table 4 presents the monthly illuminance for east and west facades.

Table 3
Glare index for Sedentary and transit conditions

Time [hr]	**Glare index**			
	21-Dec	**21-Mar**	**21-Jun**	**21-Sep**
	Winter	Spring	Summer	Fall
	Camera 1			
0900	92	39	100	37
1000	100	44	100	75
1100	100	100	100	100
1200	100	100	100	100
	Camera 2			
0900	60	66	43	41
1000	52	41	67	44
1100	58	77	61	77
1200	81	78	34	69

Results from Table 3 reveal that discomfort glare occurs in March at 0900 and 1000 and in September at 0900 for Camera1. This is as a result of using horizontal overhang for the upper window during this period. However, the tilt angle of 45^o would overcome this problem. The glare found for Camera 2 resulted from facing the window. Using lower glazing transmittance or increasing the glare threshold factor, e.g. 10 would eliminate this problem.

Table 4
The monthly illuminance levels for east and west facades

Time [hr]	Month											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	East Facade											
0900	394	485	953	451	443	439	445	450	960	646	291	371
1000	327	773	955	736	739	750	761	754	894	552	364	233
1100	462	562	565	637	645	657	667	650	562	448	365	332
1200	321	425	480	497	507	521	530	511	458	385	293	254
	West Facade											
1300	254	374	458	505	526	502	504	494	478	407	299	250
1400	365	457	532	606	626	624	616	599	552	595	435	346
1500	382	516	419	668	713	726	705	663	513	606	368	241
1600	246	622	347	405	437	442	435	408	362	420	267	272

DISCUSSIONS AND CONCLUSIONS

This paper presents the search for daylighting solutions to further exploit daylight within office buildings. Several design alternatives were proposed and evaluated. The results revealed that, although the internal light shelf affects the daylight distribution within the space, it reduces the total illuminance at the working plane (Figures 4 and 5) and has a minimal impact on glare control. The modifications of the window area and glazing properties show a significant impact on illuminance levels of the reference point.

Furthermore, using tilted overhangs offers a great opportunity to increase the admission of glare-free daylight and to reduce the use of venetian blinds. The movable shading device would be controlled by an automatic system with manual override. Architecturally, the case study has uniform facades, and the overhangs would not affect the similarity of the building appearance. However, the integration between the overhangs and building facades in addition to the other practical issues, e.g. wind forces, should be considered.

The literature review, i.e. Bordass et al. 1994, revealed that occupants typically close blinds to control solar radiation and leave them in this position, reducing daylight in the space at other times. According to the literature and based on periods when sunlight would enter the office space, it is assumed that the electric lighting would be on due to the close of venetian blinds from 0900 to 1600 for east facade and from 1300 to 1600 for west facade. Illuminance results from table 4 show an adequate illuminance level (500 lux) for the entire year, except for November, December and January. The average illuminance for such months is approximately 300 lux for both facades. Also, the average illuminance for east facade is 285 lux from 1300 to 1600. Therefore, using the final proposed alternative would almost save 70% and 45% of electric lighting for east and west facades, respectively.

Future work is required to examine the performance of design parameters via physical scale model and to focus on the integration between the building automation system, daylight-responsive control, and overhangs.

ACKNOWLEDGEMENTS

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