A methodology to simulate annual blind use in large open plan offices

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Abstract

Occupant behaviour (OB) models relating to daylighting and blind use have been developed for cellular office configurations. However, this is not the case for large open plan offices that represent different spatial, daylighting and occupancy characteristics. This paper presents a methodology to simulate annual blind use based on the daylight availability for large open plan offices. A novel multi-directional illuminance grid was used to simulate annual blind use; to account for multiple view-points and occupants. The results found that this method can be used to predict annual blind use in large open plan offices to improve building performance simulations and occupancy models.

Introduction

Optimising natural light to support visual comfort for building occupants whilst reducing energy consumption is a pertinent goal in green building design. However, occupants play a highly influential role on building performance and energy use (Asadi, Mahyuddin, & Shafigh, 2017; Fabi, Andersen, Corgnati, & Olesen, 2012; Gunay, O'Brien, & Beausoleil-Morrison, 2013; Haldi & Robinson, 2011; Jia & Srinivasan, 2015). In the case of visual comfort, occupants can make adaptive changes to electrical lights (switch on/off), blinds (occlusion) and/or localised interventions (i.e. cardboard to block view of glare or bright sources of light) to restore comfort levels (Roche, Dewey, & Littlefair, 2000). However, these adaptive actions can undermine electrical efficiency strategies (Gunay et al., 2013). Thus, occupant behaviour models (OB) have been developed to better account for behaviour leading to adaptive changes to reduce this uncertainty. The goal for OB models is to predict behaviour by realistically simulating user interactions and/or presence. Accurate models allow for realistic simulations of building system use to determine the most effective system strategies.

Current OB models relating to visual comfort and blind use have only been developed for cellular office configurations. These offices typically contain single or shared occupancy and feature one window opening and blind shade. One of the earliest OB models was developed by Newsham (1994) called *Lightswitch*. This model was based on predicting blind use and light switch on/off events to improve thermal comfort. A south facing cellular room (4.5 x 7.5 x 3m) was developed using

FENESTRA. If the solar intensity of 233 W/m² reached an occupant (based on the sunlight patch depth), the probability for blind shade operation would be 20%. This threshold was based on a field study conducted by Inoue, Kawase, Ibamoto, Takakusa, and Matsuo (1988) who found that the depth of sunlight penetration in a room was proportional to the percentage of blinds closed in a room. Similarly, Reinhart (2004) developed a model called *Lightswitch-2002* to predict manual blinds and electrical light switch on/off events for cellular offices using a stochastic approach. The control algorithm for blind use prediction was based on solar irradiance from previous field studies. If 50 W/m² reached the workstation, blinds would be fully lowered and re-opened every morning the following day upon occupants' arrival to work.

The issue is that these models may not be suitable to predict blind shade use in large open plan offices. Unlike cellular offices, occupants in open plan offices have exposure to both natural and electrical light sources from multiple direction and orientations. Modern open plan offices are designed with undivided walls to accommodate the greater portion of the office population. Predominate features such as floor to ceiling height glazing/windows along the building perimeter are maximised to optimise the benefits of natural light (Green Building Council of Australia, 2008; Leadership in Energy and Environmental Design, 2013). Generally, to provide sufficient electrical lighting in offices, 320 lux (maintained illuminance) is recommended for screen-based activities for either the horizontal or vertical work-plane. For daylighting control strategies, blind shades are recommended to prevent visual discomfort or glare (Australian Standards, 2006, 2008). In the case of green buildings, blind shades are required to achieve a visual light transmittance of $\leq 10\%$ (Green Building Council of Australia, 2017). However, in large open plan offices that have a window to wall ratio (WWR) as great as 90%, the vertical illuminance would be a considerable factor for blind use modelling; particularly when work activities are conducted on vertical display terminals (VDT). Thus, existing thresholds used to predict blind shade use may not be optimal if the directionality of the occupants' dominant facing position is on the vertical plane. These considerations would need to be accounted for in OB models particularly when there are different occupant workstation locations, multiple view orientations and daylight sources. This has yet to be explored. Such an unaccounted difference spatially and characteristically

would make blind use simulations inaccurate (Hoes, Hensen, Loomans, de Vries, & Bourgeois, 2009). However, one challenge is providing a way to simulate blind use that would consider the aforementioned factors. To this end, the aim of this study was to propose a simulation methodology for annual blind use for large open plan offices; using a novel approach to simulate both the horizontal and vertical illuminance. The simulation methodology also aimed to consider the practical issues of capturing illuminance measurements in a real office setting populated by building occupants to reflect real world conditions.

Simulation methodology

Figure 1. (a) Case study of a typical large open plan office in Brisbane, Australia. (b) North-west portion of the office was examined using a multi-directional illuminance grid indicated in red.

A large open plan office located on the seventh floor in a subtropical climate in Brisbane, Australia (27°28'41.921" N, 153°1'45.632" E, atl.11m) was selected as a case study.

The building was modelled with no neighbouring buildings. For testing the methodology, only a section of the North-West portion of the office was examined (approx. 15.4m x 7.2m x 3m) (refer to Figure 1a). Although a portion of the office was investigated, the method can be extended to simulate an entire floor. The office featured daylight penetration from floor to ceiling height glazing panels (non-operable windows) and solar blind shades (Venetian with no slats). A total of eight workstations separated by shared privacy screens (height 1.13m) were examined (see Figure 1b). The methodology adopted a non-linear algorithmic approach using Grasshopper in Rhinoceros (Rutten, 2014). This approach was selected for its parametric ability to create parameters that can be adjusted and applied over other projects (Wagdy, 2013; Wagdy & Fathy, 2016).

Further, the methodology was developed to mimic the sensor points of a real datalogger currently deployed in field studies (see Figure 3). These dataloggers were built to capture illuminance in five directions (one horizontal illuminance sensor on the upper cube surface, and 4 vertical illuminance sensors) simultaneously in large open plan offices. This is to determine illuminance thresholds to predict blind opening percentages based on occupant locations. Hence, the proposed methodology was aimed to provide a framework to simulate illuminance values extrapolated from practical and realistic scenarios. In this study a total of 40 sensor points were simulated. The algorithm was developed across three stages (see Figure 2). In stage 1, a novel multi-directional illuminance grid was created to simulate the daylight availability from horizontal and vertical sensor points. Stage 2 involved applying a sorting and grouping logic to both blind shades and sensor points. This was to address the issue of deciding which blind shade(s) and sensor point(s) would be triggered. Stage 2 defined illuminance thresholds to trigger blind shade opening percentages; to create a series of annual blind shade schedules. To compare results, *Lightswitch-2002* by Reinhart (2004) was used to produce the same blind schedule. The following sections further describe the simulation methodology in detail.

Stage 1: multi-directional illuminance grid

To simulate annual blind use, a multi-directional illuminance (lux) grid was first developed (see Figure 4). First, parameter points were arbitrarily defined to construct the points and to define the location of each sensor grid. A total of eight grids were placed on top of the privacy screens separating occupant workstations (mounting height 1.13m). This location was considered as the most realistic, consistent and practical position in real-world conditions.

Figure 2. Simulation methodology workflow in three stages

Five vector rays were constructed for each grid to simulate five sensors (horizontal and vertical planes). Each vector ray was assigned with an identity number (0, 1, 2, 3, 4, etc.,) using the point parameter function; totalling up to forty sensor points. To determine which blind shade was controlled by which sensor point, a 90° geometrical cone was projected from each sensor, to intersect with the nearest glazing panel. This defined the sensors' control range, which was set to 5m for the purposes of this study.

(a)

(b)

Figure 3. (a) Dataloggers used to capture empirical data in large open plan office (currently used in field studies). (b) Multi-point illuminance grid based on occupant workstation locations to mimic dataloggers.

Figure 4. Multi-point illuminance grid simulating five sensor points: four vertical points and 1 horizontal.

Stage 2: sorting and grouping logic

An annual daylight simulation was initialised to calculate the hourly mean illuminance at each sensor point. This was simulated using an existing local weather data file

and parameters described in Table 1. Radiance parameters used were: -aa .1 -ab 7 -ad 4096 -ar 512 -as 1024 -dr 2 -ds .2 -lr 12 -lw .001 -dj 0 -lr 6 -sj 1 -st 0.15. The purpose of this step was to calculate the daylight availability for all forty sensor points without blind shades; to apply illuminance thresholds to trigger blind opening percentages for stage 3. A sorting and grouping logic were applied to determine the most likely sensor to control the blind shade(s). Identifying who would control this in a cellular office would be straight forward. However, this methodology would need to account for multiple occupants and to assume that they all share *all* blind shades. This was reflected in the overlap in the sensors' control range; where multiple sensor points control (intersect) the same blind shades (see Figure 5). Therefore, the calculated mean illuminance for each sensor point was sorted in multiple lists based on the order of performance (highest to lowest mean annual illuminance). The sensor(s) that would trigger the blind shade was therefore based on the sensor(s) that would read the highest illuminance value. A selection criterion was then reversed so that the glazing panels were the selector rather than the sensor points; to sort through the highest performing sensor(s) to trigger blind occlusion.

Table 1. Building and material parameters

Space parameters		
Floor level	7 th floor (+22.00m)	
Gross floor area	2712.1 m ²	
Space area (studied)	118.1 m ²	3m x 16.8m x 7m
Internal surface materials		
Walls	Reflectance	50%
Ceiling	Reflectance	80%
Floor	Reflectance	20%
Furniture	Reflectance	50%
Window parameters		
WWR	90%	
Glazing	Transmittance	80%
Window frame	Reflectance	Metal diffuse
Shading parameters		
Blind Type	Manual roller blinds	
Blind Material	Transmittance	4%
Multi-point illuminance grid		
Control range	5m	

Stage 3: thresholds and blind scheduling

To date, there are no agreed thresholds nor metric to define daylight tolerance levels that would trigger occupants to change blind shade settings. Previous studies that have investigated this, have reported different results.

As mentioned earlier, Newsham (1994) used the solar intensity of 233 W/m² as the predictor variable whereas Reinhart (2004) found 50 W/m². Conversely, Lindelöf and Morel (2008) adopted 800 to 1200 lux on the horizontal work-plane to estimate visual discomfort in small offices for both blinds and lighting controls in their probability model, which was consistent with a probability model developed by Haldi and Robinson (2010). These findings were not applied in this study for the illuminance thresholds; since this study assumed that the vertical illuminance would also be a significant predictor variable. This was to account for the vertical viewing position and directionality of the occupants.

Figure 5. Example of sensor points selecting the same glazing panels. (a-d) vertical illuminance sensor points and (e) horizontal illuminance from multi-illuminance grid 1. Sorting and grouping logic applied to select sensor to control blind shade.

In this study, the illuminance thresholds were arbitrary to complete the simulation workflow.

However, these parameters can be easily adjusted based on new evidence as derived from ongoing field studies. The illuminance thresholds were applied to predict the blind opening percentage for each blind shade to produce an annual blind shade schedule. This schedule describes the blind shade status as either 0 (fully opened), 0.25, 0.5, 0.75 or 1

(fully closed) at an hourly interval. Blind shade triggering events were set in four different states (for both horizontal and vertical sensor points) that was passed through custom logical gates in Grasshopper:

- 0-200 lux triggers 100% fully opened
- 200-600 lux triggers 75% opened
- 600-1200 lux triggers 50% opened
- 1200-1800 lux triggers 25% opened
- >1800 lux triggers 0% opened

The final daylight simulation was performed using the same parameters in Table 1. The results were discussed in detail below.

Results and discussion

A methodology to simulate annual blind use for large open plan offices was presented, with the goal to provide a framework that can account for the practical implications of extrapolating real-world data. The results show that using a multi-directional illuminance grid to estimate the daylight availability at multiple workstation locations can provide more detailed information about blind use patterns for multiple occupants. This method accounted for vertical illuminances exceeding >1800 lux that would otherwise not be detected with existing models (see Figure 6). Previous studies that have focused on blind shade prediction in cellular offices, typically feature only one window and considered either the horizontal illuminance or solar irradiance as the predictor variable. However, for large open plan offices that have a WWR as great as 90%, multiple view-points to multiple glazing panels (or windows) should be a considered variable to predict blind shade use. This is particularly so if the main work activities are conducted on VDT screens. In comparison to cellular offices, simulating blind shade use is much more complex in large open plan offices that are undivided by internal walls. It would require determining which occupant would be most likely to operate the blind shade(s) and deciding which blind would be occluded. In this case, empirical data would be necessary to further explore this issue.

Figure 6. Example of annual illuminance for one vertical sensor point exceeding >1800.

The proposed methodology was compared with *Lightswitch-2002*. DIVA in Grasshopper was used to simulate an annual blind shade schedule using the same parameters in Table 1. Two annual blind shade schedules were produced from each approach by simulating only one blind shade. Schedules were simulated based on the annual mean illuminance (without blind shades) from Figure 7a.

To make the comparison, the illuminance thresholds were set to only two states: <600 lux (fully opened) and >600 lux (fully closed). This was because DIVA was only able to define blind states based on integers (0=fully closed, 1=fully opened) and not floating values (i.e. 0.25).

Figure 7. Simulating one sensor point and blind shade to compare annual blind shade schedule with *Lightswitch-2002*. (a) Initial simulation to obtain annual daylight availability (without blind shades). (b) Annual blind shade results using the proposed methodology (vertical illuminance). (c) Annual blind shade results using *Lightswitch-2002* (solar irradiance).

The results showed that the proposed methodology predicted annual blind shade use more frequently throughout the day across the entire year as shown in Figure 7b (black = 100% closed and white = 0% opened). On the other hand, *Lightswitch-2002* predicted blind shade use only between May and September as shown in Figure 7c. The difference was due to the unit of measurement, where *Lightswitch-2002* predicted blind shade use based on solar irradiance (50 W/m²); detecting only the most critical times of the year in which the sun would be at its lowest angle. On the other hand, the proposed methodology was able to detect additional brightness (i.e. reflectivity, diffused light etc.) that would influence blind shade use.

Figure 8. Further comparison between both approaches using the daylight availability (illuminance values available after blinds are drawn from Figure 7). (a) Proposed methodology - annual vertical illuminance values still available after blinds were drawn from Figure 7b. (b) Proposed methodology - annual blind shade use based on the available vertical illuminance from (a). (c) *Lightswitch-2002* - annual horizontal illuminance values still available after blinds were drawn from Figure 7c. (d) *Lightswitch-2002* - annual blind shade use based on the available horizontal illuminance from (c).

To further this point, an additional comparison was made between both approaches. In *Lightswitch-2002*, the horizontal illuminance is automatically calculated from the solar irradiance as part of its output. This was extracted (see Figure 8c) to simulate a subsequent blind schedule shown in Figure 8d. This was also repeated using the proposed methodology as shown in Figure 8a (annual vertical illuminance) and Figure 8b (annual blind schedule). This comparison was only made possible since the blind shade was set to the same opacity realistic of solar blind shades (5%). The results confirm that blind shade use would be more frequent when simulating the illuminance in *Lightswitch-2002*. Figure 8c shows the horizontal illuminance levels exceeding >1800 that would not have otherwise been detected using the solar

irradiance (note: illuminance values were based on the daylight availability after blinds were simulated from Figure 7b).

Overall, the results highlighted two important findings. First, illuminance was able to detect more frequent blind use throughout the year compared to solar irradiance. Second, the vertical illuminance was found to

be as pertinent as the horizontal illuminance in detecting high illuminance levels and the variation between each glazing panel. Further, in comparison to *Lightswitch-2002* the proposed methodology was more flexible in simulating the daylight availability in large open plan offices. DIVA employs a 7m horizontal grid depth from the building perimeter with a 1.5 x 1.5 sensor radius spacing.

Table 2. Results of the blind schedule simulation for multi-illuminance grid 0 (refer to Figure 3).

Multi-illuminance grid 0										
Time	Sensor 0		Sensor 1		Sensor 2		Sensor 3		Sensor 4	
	E_h	Opening %	E_v	Opening %	E_v	Opening %	E_v	Opening %	E_v	Opening %
24:00:00	0	0	0	0	0	0	0	0	0	0
01:00:00	0	0	0	0	0	0	0	0	0	0
02:00:00	0	0	0	0	0	0	0	0	0	0
03:00:00	0	0	0	0	0	0	0	0	0	0
04:00:00	0	0	0	0	0	0	0	0	0	0
05:00:00	68	0	220	25	288	25	104	0	152	0
06:00:00	416	25	1292	75	1688	75	612	50	896	50
07:00:00	832	50	2584	100	3328	100	1204	75	1792	75
08:00:00	1240	75	3864	100	4968	100	1796	75	2640	100
09:00:00	2064	100	5832	100	6420	100	2408	100	3368	100
10:00:00	2112	100	6292	100	7220	100	2632	100	3872	100
11:00:00	1624	75	5320	100	7328	100	2520	100	4088	100
12:00:00	1976	100	6428	100	9272	100	3192	100	4640	100
13:00:00	1536	75	5076	100	7296	100	2504	100	3932	100
14:00:00	1376	75	4560	100	6896	100	2324	100	3560	100
15:00:00	1088	50	3596	100	5496	100	1892	100	2820	100
16:00:00	672	50	2224	100	3440	100	1188	50	1772	75
17:00:00	280	25	920	50	1348	75	472	25	696	50
18:00:00	32	0	104	0	136	0	48	0	72	0
19:00:00	0	0	0	0	0	0	0	0	0	0
20:00:00	0	0	0	0	0	0	0	0	0	0
21:00:00	0	0	0	0	0	0	0	0	0	0
22:00:00	0	0	0	0	0	0	0	0	0	0
23:00:00	0	0	0	0	0	0	0	0	0	0
24:00:00	0	0	0	0	0	0	0	0	0	0

* E_h = horizontal illuminance, E_v = vertical illuminance and % = blind opening percentage (0% fully opened, 0.25, 0.5 half opened, 0.75, 1.0 fully closed).

Although this might work for smaller offices, it would be hard to adapt this method for large offices, which need a flexible method to configure optimal seating positions for multiple building occupants. This was noted by Reinhart (2004). In addition, one other limitation with DIVA was that it predicted only two states: fully opened (100%) and fully closed (0%). If DIVA was able to read floating values rather than simplifying blind opening percentages, it would be more reflective of occupants occluding a variety of opening percentages (see Table 2). By using this approach, blind shade use can be deterministically predicted by accounting for multiple workstation locations and view-points.

This was achieved by defining the range of the geometrical cones (5m) in order to assign and group each sensor point based on its intersection with each glazing panel. If multiple sensors shared the same blind shade, the sensor that read the highest illuminance value would be

defined as the most likely occupant to lower the blind shade(s).

Figure 9. Example of DIVA simplifying annual blind shade use from Figure 8b by using integers.

One limitation to this approach was that it did not consider the adaptive responses which would categorise occupants into *active* and *passive* users, as highlighted in literature (Haldi & Robinson, 2008, 2011). For instance, if one sensor from a datalogger read >1800 lux and a different dataloggers' sensor read between 1200-1800 lux, the active user would be the occupant to occlude the

blind shade, irrespective of the illuminance value. That is, some occupants are more likely to interact with blind shades than others. The authors are currently conducting field studies to observe the relationship between these variables in real world settings, which will be published in a subsequent paper.

The simulation results can be found in the following link: <https://goo.gl/kzUQYJ>.

Conclusion

This paper presented a methodology to simulate annual blind use for large open plan offices. A novel multi-illuminance grid was developed to account for multiple occupant workstations and view-points and blind shades. The results showed that by using this method, each blind shade can be simulated to show the opening percentage at an hourly interval across an annual year. In comparison to previous blind use models, this method realistically accounts for the practical implications of collecting empirical data in real-world scenarios, in order to facilitate comparison to field measurements. Further, when comparing this method with existing blind use models, the results found that the illuminance highlighted periods for additional shading. The next stage is to use field results to refine thresholds and validate this approach.

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