# TIME-LAPSE PHOTOGRAPHY AND IMAGE RECOGNITION TO MONITOR OCCUPANT-CONTROLLED SHADE PATTERNS: ANALYSIS AND RESULTS

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## ABSTRACT

This paper presents a high-level overview of a methodology for analysing window shade use in existing buildings. Time-lapse photography is paired with a robust image recognition algorithm to facilitate assessment of shade use and identify any possible trends. The methodology applied on a high-rise building consisting of multiple open plan offices. The analysis showed that the mean shade occlusion and the shade movement rate depend on façade orientation, with the near-south façade having the highest values and the near-north façade having the lowest ones. An average shade use rate of 0.5/day was observed, with the 72% of the shades never adjusted, throughout the period of observation.

## INTRODUCTION

Occupants tend to be inactive shade users with only 40% being readjusted any given day, in one study, with a range of use from daily to never (Inoue et al., 1988). Instead of being highly-responsive to glare conditions, occupants tend to leave their shades in a position that "causes the least trouble"(Bordass et al., 2001). As a result, buildings tend to have much higher mean occlusions than instantaneous weather conditions would suggest. This leads to unnecessary electric lighting use and ultimately inflates energy use relative to what designers might expect.

In order to better quantify occupant behaviour with regards to dynamic shading device control, about a dozen researchers have studied their use in real buildings for a duration of days to six years (O'Brien et al., 2013). The ultimate purpose of the researchers ranged from a mere understanding on the key motivators of shade control to establishing a detailed stochastic model based on one or more environmental variables. The studies have generally concluded that solar-related factors (namely glare) are the greatest motivators for shade movement and that indoor temperature has little impact on it. Those without air conditioning do use shades to help control thermal comfort. Occupants with easier access to the shades controls tend to be more active users (Sutter, et al., 2006). Façade orientation and solar penetration depth are among the best predictors of mean shade occlusion. The literature consistently reports that south-facing façades have the greatest mean occlusion and north-facing façades have the least. However, two of the key metrics – mean shade occlusions and shade movement rate – vary considerably between studies and anomalies are commonplace. Many researchers have acknowledged that their results are skewed by unique building characteristics or occupancy patters, including: anidolic reflectors, multiple sets of blinds per space, multiple occupancy, views and privacy, and automated lighting controls, to name a few.

Thus, there is a sufficient lack of understanding in manually controlled shade use to justify further and more extensive studies. The objective of this work is to identify and quantify possible triggers and tendencies on manually-controlled shades' movement and positions, through a revised observational methodology. The long-term objective of this research project is to develop occupant behaviour models for shading controls that can be universally applied to building performance models and advanced shade controls.

## METHODOLOGY

There are three major categories of techniques currently existing to monitor occupant-controlled shade patterns: i) time-lapse photography of the exterior building façade, ii) shades position (electro-mechanical) sensors and iii) building walkthroughs. This paper focuses on time-lapse photography on roller shades; a non-invasive technique that allows large sample sizes to be captured. Researchers (Rea, 1984) have found that image analysis is a very time-consuming process and they often reduce the sample size – either spatial or temporal – to reduce effort. However, if the image processing is automated, it could be a low-cost, efficient process. As initially stated by O'Brien et al. (2010), the technique can be limited mainly by weather conditions (e.g. rain or fog), visual obstructions and veiling reflections on the building façade.

The general methodology can be summarized into four major steps: i) time-lapse photography, ii) image pre-processing, iii) image recognition and iv) data analysis. Figure 1 illustrates the major steps.

### Time-lapse photography

A digital camera, with sufficient image resolution (3 megapixels and above, depending on the façade size) captures instantaneous shade positions of an entire building façade. A polarizing filter can be used to minimize veiling reflections. The photographic vantage points should be fixed and be as close as possible to normal to the façade surface, to avoid any image distortion due to photographic angle. In addition, the low shade operation frequency found by most studies (Rea, 1984, Inoue et al., 1988, Pigg et al., 1996, Inkarojrit, 2008) suggests that time-lapse photography should extend over a period of a few days to a few weeks and a sampling rate of no less than twice daily.

### Image pre-processing

Each image is taken or converted to greyscale to reduce complexity in the image recognition algorithm. The pixel coordinates of the corners of the building façade should be specified. If the vantage points are not fixed, the pixel coordinates have to be identified for each individual image. A projective transformation of each image should be performed, in order to ensure equal façade geometries (e.g. location, width and height of windows) through time-lapsed images and to facilitate the next step.

### Image recognition

Each image is processed using an image recognition program that was custom-built in MATLAB. The program has the ability to determine the individual windows and recognize the position of the shade, due to pixel intensity jump between shaded and unshaded part of the window. For windows for which the shades were fully open or fully closed, this method cannot be used, since the pixel intensity jump only occurs at the top and bottom of the window. To resolve this, the pixel intensity (grayness) of the shade is estimated based on the neighbouring shades (three window radius). This intensity is then used as a threshold to predict whether the current shade is fully up or fully down.

The position of each shade is translated to a fraction of unity, where 0 is for fully open and 1 is for fully closed shade. An *m*-by-*n* matrix is generated, where *m* is the number of shades per floor and *n* the number of storeys. Each matrix element represents a fraction closed of a shade.

As the pixels' intensity of shades cannot be universally defined due to sunlight patterns, reflections and possible obstructions, the program should allow manual correction (depending on the required accuracy), in order to minimize errors on the shades' position. A detailed semi-automated image recognition process can be found on O'Brien et al., (2010).

### Data analysis

The data analysis can provide, but is not limited to, the following metrics.

- Mean Shade Occlusion (*MSO*), defined as the average fraction that the shades are closed, for the façade of interest. It is given by:

$$MSO = (\frac{1}{n})\sum_{i=1}^{n}(p_i) \tag{1}$$

- Shade Movement Rate (*SMR*), defined as the fraction of shades that are moved between two discrete times (Inoue et al., 1988). It is given by:

$$SMR = (\frac{1}{n})\sum_{i=1}^{n}(N_i) \tag{2}$$

where $(N_i) = countif\left(\frac{dp_i}{dt} \neq 0\right)$ (3)

- Shade Use Ratio (*SUR*), defined as the ratio of shades moved *j* times (*j*=0,1,2,…), during a period (e.g. daily). It is given by:

$$SUR_j = \frac{M_j}{n} \tag{4}$$

All metrics can be expressed as a function of time of the day, season, solar radiation (direct and/or diffuse) incident on or transmitted though façade, façade orientation and solar penetration depth (Reinhart and Voss, 2003).

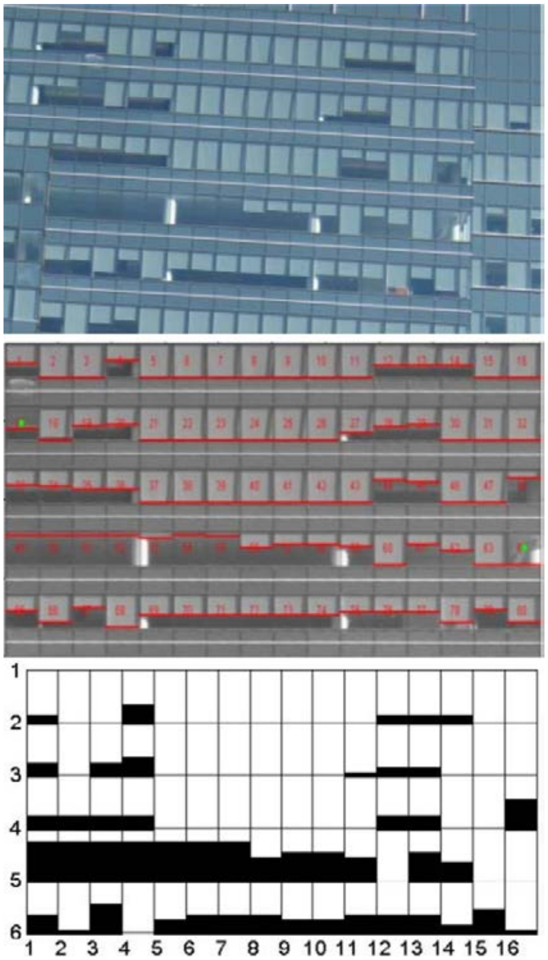

*Figure 1 The major steps of time-lapse photography technique: time-lapse photography (top), image pre-processing (middle) and image recognition (bottom).*

## CASE STUDY

A high-rise commercial office building in Montreal was selected as a large scale (more than 1200 windows) case study. The building consists of two towers of similar height. The building orientation, the neighbouring buildings and their height as well as the facades of interest are illustrated in Figure 2.

The curtain wall façade (Figure 1) consists of 0.8 m height of opaque spandrel on the lower part, and 1.9 m height of fixed double glazed window on the upper part (estimated visible transmittance of 0.5-0.6), on each storey. Roller shades (visible transmittance of 0.05) are installed on each window, which can be manually and individually controlled by a pulling chain.

Each storey has several open plan offices with access to windows with one or more orientations. The office depth from the façade can vary from 9 m to 18 m. Office cubicles of 1.1 m, 1.4 m and 1.7 m height (with or without transparent separations) are distributed throughout the offices. The cubicles closest to the façade are located 0.7 m away.

The walls and seperations are light grey (estimated reflectance of 0.6-0.7) while the floor carpet appears with grey geometrical patterns (estimated reflectance of 0.4-0.5).

Direct-indirect suspended fluorescent luminaires are used on each office, controlled by occupancy sensors and manual on-off switches.

## TIME-LAPSE PHOTOGRAPHY AND IMAGE RECOGNITION

A time-lapse photography technique was applied on the case study. A tripod-mounted Canon PowerShot A480 was used to capture the time-lapsed images, from the street level. The vantage points for each façade are illustrated on Figure 2 (e.g. "ne" vantage point for the NE façade and so on).

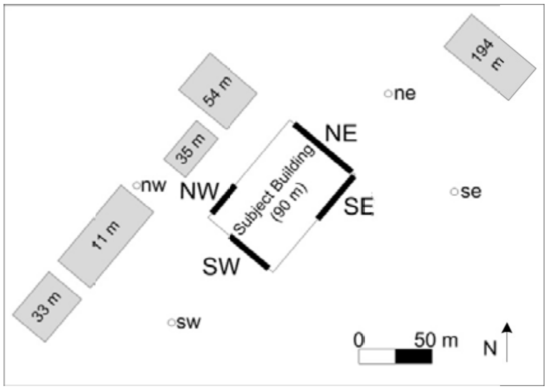

*Figure 2 Plan view of the building location, with the façades of interest (bold black lines). Building heights are noted.*

Table 1 summarizes the number of windows and floors per façade orientation that were photographed. The facades of interest represent one third of the total building façade and there were chosen in order to minimize the photographic angle, veiling reflections and obstructions. An hourly sampling rate was chosen for this study, driven by the hourly weather data available and to compromise between temporal resolution and effort (O'Brien et al., 2013). The time-lapsed images were taken during the weekdays of 29 January, 27 May and 4 December, between 8AM to 6PM. A weather file (Hydro-Quebec, 2013) generated based on a data available from a local weather station (located 13 km from the subject building) was used. Figure 3 presents the global horizontal solar radiation and the incident solar radiation on the SW façade, as it was estimated for the three sunny days, using EnergyPlus.

*Table 1*
*Summary of facades of interest*

| NAME OF FAÇADE | ORIENTATION | NUMBER OF WINDOWS STUDIED | NUMBER OF STOREYS |
|---|---|---|---|
| NE | N35°E | 375 | 15 |
| SE | S55°E | 432 | 18 |
| SW | S35°W | 208 | 13 |
| NW | N55°W | 216 | 12 |

To assess the images, a projective transformation was applied to ensure equal façade geometries. The images were processed and transformed to a matrix, using the image recognition program. Less than 4% of the shade positions required manual correction, demonstrating the robustness of the algorithm. These were mostly identified by the software as being uncertain.

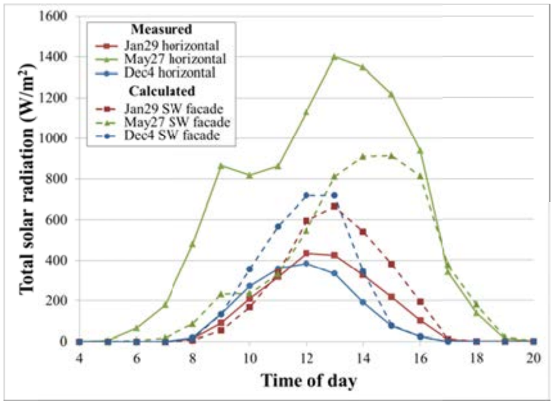

*Figure 3 Global horizontal solar radiation and incident solar radiation of the SW façade*

As the images were taken from the street level and due to the 90 m building height, the photographic angle was too steep for the image recognition algorithm to identify shade position movements that varied less than 10%. Therefore, any shade position movements less than 10% were discarded. This is considered insignificant since such adjustments have minimal impact on overall solar transmittance and ultimately comfort and energy use. To overcome this, the vantage points could be located on elevated locations (e.g. top of the roof of a neighbouring building).

Finally, the data was statically analysed in order to identify possible patterns on the occupant-controlled shades.

## RESULTS AND DISCUSSION

### Mean Shade Occlusion

MSO is one of the most useful metrics for feeding occupant behaviour models, as it represents the preferred shade position. It signifies the average energy performance of the façade (SHGC, U-value and solar transmittance) but it is not always a good indicator of the daylighting levels, since they highly depend on the position of the individual shades. Thus, beyond the MSO, for this study the first quartile (25% of shade occlusion), median (50% of shade occlusion) and third quartile (75% of shade occlusion) were reported, indicating the variation of shade positions on the façade of interest.

The analysis showed that MSO is nearly constant during the period of a day (daily effect) (Figure 4, on the last page) and between different days through a year (seasonal effect), within 3 percentage points, for all the façade orientations studied. Similar findings were reported by Rea (1984). On the contrary, Inoue et al. (1988) reported that MSO was relatively high on east facades during occupants arrival and it gradually decreased throughout the day, while the opposite occurred on the west facades. Zhang and Barrett (2012) found a significant seasonal variation on MSO, for non-north facing facades. Nonetheless, all three studies were performed on venetian or vertical blinds.

Previous studies (Inkarojrit, 2008, Pigg et al., 1996 and Rubin et al., 1987) found that the highest values of MSO occurred on near south-facing facades, while near north-facing ones were most likely to have the lowest MSO. The ratio of south-to-north MSO was found to be as high as 5.0 (Mahdavi et al., 2008), under sunny conditions. The current study found a near south-facing (SW) MSO of 84%, a near-east (SE) and near-west (NW) MSO of 70% and a near-north (NE) MSO of 60% (Figure 5); a south-to-north MSO ratio of 1.4.

One would expect that solar radiation and solar geometry would have a significant impact on shades' position and thus, on MSO. Lindsay and Littlefair (1992) found that MSO is higher on sunny days versus cloudy ones. Reinhart and Voss (2003) and Inoue et al. (1988) reported that solar penetration depth is a good indicator of MSO; as the solar penetration increases, the MSO increases. On the current study the MSO was found to be independent of global horizontal solar radiation, incident solar radiation on façade, direct solar radiation incident on façade, transmitted solar radiation through façade and solar penetration depth (Reinhart and Voss, 2003). Note that all irradiance values were estimated based on the available weather file, using the Perez sky model (Perez et al., 1990). Moreover, the images were taken on sunny days only. Any variation of MSO between sunny and overcast days would not become apparent on this study.

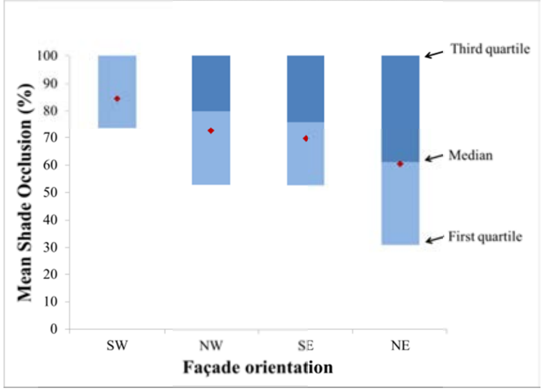

*Figure 5 Mean Shade Occlusion as a function of façade orientation*

### Rate of change

Literature suggests that occupants rarely move their shades in a period of day. Reported average shade use rates vary from 0.05/day (Lindsay and Littlefair, 1992) to 0.7/day (Sutter et al., 2006). The current analysis showed an average shade use rate of 0.5/day, while 72% of the shades were never adjusted ($SUR_0$=72%), 12 percentage points higher than the highest reported value (Inoue et al., 1988). An average of 12% adjusted their shades 1/day ($SUR_1$=12%), while 10% adjusted 2/day ($SUR_2$=10%) (Figure 6). Despite variations, no dependence of $SUR_i$ on façade orientation was apparent.

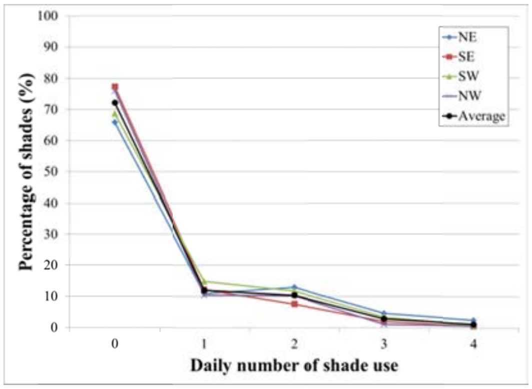

*Figure 6 Shade Use Ratio for the four façade orientations*

### Shade Movement Rate

SMR is useful for identifying the triggers that made the occupants readjust their shades, but it does not indicate the direction of the action (raising or lowering the shades). On this study, the direction of the shade movement is noted, when necessary.

Pigg et al. (1996) observed that the SMR was higher at south facing façades but not at a high level of statistical significance. Similarly, one would expect the lowest SMR to appear on the near-north facing façade, due to admission of diffuse and consistent daylight. However, due to a high percentage of stationary shades, SMR are so low that it is difficult for someone to draw conclusions for the trends on shade movements. Inoue et al. (1988) overcame this issue by eliminating the stationary shades from his analysis and focusing on the moved shades, in order to identify potential triggers on shade movement. A similar approach is followed on this study with emphasis on the moved shades. This method has an additional advantage. It eliminates any uncertainties caused by lack of direct information on office occupancy.

The current analysis found that SMR for the near-south facing façade could be up to 5 times higher than the near-north facing one, while the SMR values for near-east and near-west façade lie in-between (Figure 7). Fewer than 12% of the shades are moved every hour (SMR<12%), with an average SMR value of 8.1% for near-south, 5.4% for near-west, 7.4% for near-east and 2.9% for near-north façades, indicating that façade orientation might have an impact on shade movement.

Many studies agree that SMR increases at certain times of the day. Haldi and Robinson (2010) reported SMR peaks upon arrival at the office. Zhang and Barrett (2012) observed SMR increasing as global horizontal radiation reached its peak value. Figure 8 (shown on last page) presents the daily trends on moved shades for the four façade orientations. Note that no results were reported for NE and NW façades, between 5PM-6PM as the total number of moved shades were fewer than 10 and thus no results could be drawn due to low statistical population. The peak of daily SMR occurs between 12PM-3PM (Figure 7), with 60%-70% of the moved shades being towards lowering, for all orientations (Figure 8). Relatively high SMR values are noted between 8AM-9AM, for the SE and SW façades, with the tendency to raise the shades (60%-95% of the moved shades). This contradicts with Inoue et al. (1988) that noted that occupants lower their near-east facing shades upon arrival at the office, in order to prevent glare caused by the low altitude morning sun.

Finally, no direct correlation or threshold was evident between SMR and irradiance values (global horizontal, incident on the façade, transmitted through façade) or solar penetration depth.

Regarding percentage of movement for moved shades, 35% of the adjusted shades were moved by one third of the window height (Figure 9), indicating that any occupant-behaviour model developed on shade controls should include at least 4 position steps, (fully closed, 1/3 open, 2/3 open, and fully open). Noted that, any shade position movements less than 10% were discarded, due to high photographic angles of incidence.

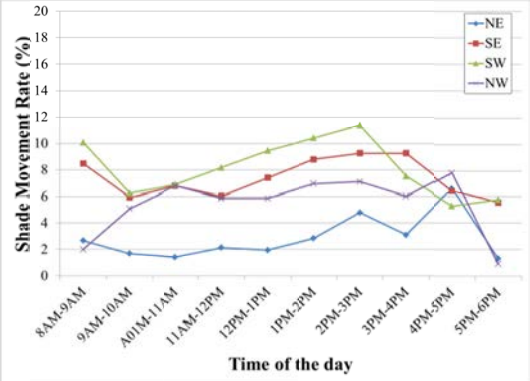

*Figure 7 Daily SMR for the four façade orientations and averaged for the three days*

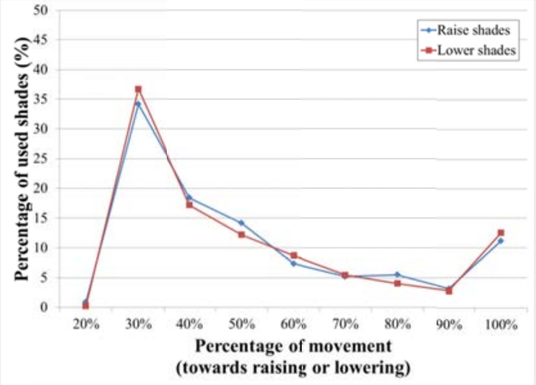

*Figure 9 Percentage of movement between moved shades, averaged for the three days*

### On view to outdoors

It is difficult to quantify any effects that view to the outdoors has on occupants' preferences on shade position, using only direct observation techniques such as time-lapse photography. The authors support the notion that occupants do put significant thought into positioning their shades (Rubin et al., 1987). In conjunction with the infrequent use of shade, the lack of correlation or threshold between MSO or SMR and irradiance values or solar penetration depth, and the fact that many studies identified the desire of occupants to outside view (Veitch and Farley, 2001) the following hypothesis is made: The shades were positioned down to 70%-80% (MSO=70%-80%) in order to place the bottom of the shade near the horizon line. This way, the view field of an average-height occupant, seated 1 meter from the façade, will be protected from the bright sky; while he will maintain view to the outdoors (Figure 10).

Unfortunately, this hypothesis can be only tested with directly interviewing the occupants; this action was not taken on this work. Future studies should consider validating or rejecting this hypothesis on their analysis and possibly providing an answer on why occupants rarely readjust their shades.

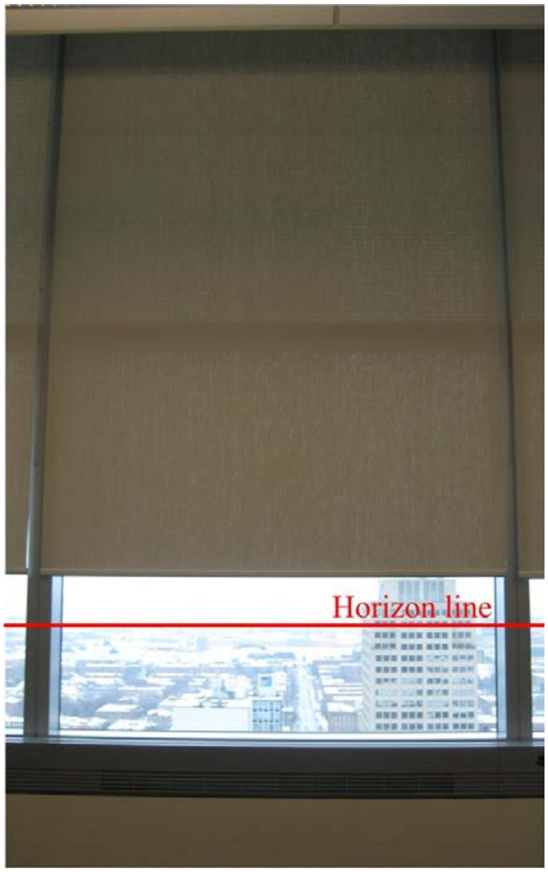

*Figure 10 Window on the SE façade, with an indication of the horizon line*

## CONCLUSIONS

An alternative approach on time-lapse photography technique was presented. A semi-automated image recognition algorithm was created, able to process time-lapsed images of large-scale façades. The new approach was applied to a study case of a high-rise building, consisting of open plan offices. The study found that façade orientation influences the average shade position as well as frequency of movement. The highest Mean Shade Occlusions were observed on the near south-facing façade (MSO=84%), while the lowest was on the near-north facing façade (MSO=60%). Similarly, Shade Movement Rate for the near-south facing façade was observed to be up to 5 times higher than the near-north facing one, while the SMR values for near-east and near-west façade lie in-between.

While it was found that façade orientation has a major impact on both MSO and SMR, this is almost certainly related to solar intensity and geometry patterns and not merely the orientation. This notion is supported by the observation that the peak of daily SMR for all façade orientations coincide with the daily peak of global horizontal radiation (between 12PM-3PM), with 60%-70% of the moved shades being lowered. However, no direct correlation or threshold was evident between MSO, SMR and irradiance values (global horizontal, incident on the façade, transmitted through façade) or solar penetration depth. This is possibly because the monitoring period was throughout clear days, while it should include intermediate as well as overcast sky conditions.

It was shown that occupants make little effort to change their shades, confirming previous studies. An average shade use rate of 0.5/day was observed, with the 72% of the shades never adjusted, throughout the period of observation. Considering that the study took place on an open plan office building, the inactivity might be due to the fact that the occupants tend to be "more loose on their environment", in a shared space (Boyce, 1980).

Finally, the study noted that 35% of the adjusted shades were moved by one third of the window height, indicating that any occupant-behaviour model developed on shade controls should include at least 4 position steps. Note that the findings of this study should be taken within the context of open plan offices, under sunny days.

### Future Work

In the future, observation periods should be extended to several weeks, including variation of weather conditions and if possible, spread throughout a year, to capture any seasonal effects on shade patterns. An effort should be made to develop mathematical relationships and statistical occupant behaviour models that could be employed by building simulation programs and shade controls, realistically replicating occupants-controlled shade patterns.

## NOMENCLATURE

$M_j$ = ratio of shades moved j times, on a period (e.g. daily)

MMR = Mean Movement Rate

MSO = Mean Shade Occlusion

n = total number of shades

N = number of shades moved between two discrete times

p = fraction closed of shade

SMR = Shade Movement Rate

SUR = Shade Use Ratio

t = timestep

*Subscripts*

i = shade index number

j = shade use index number

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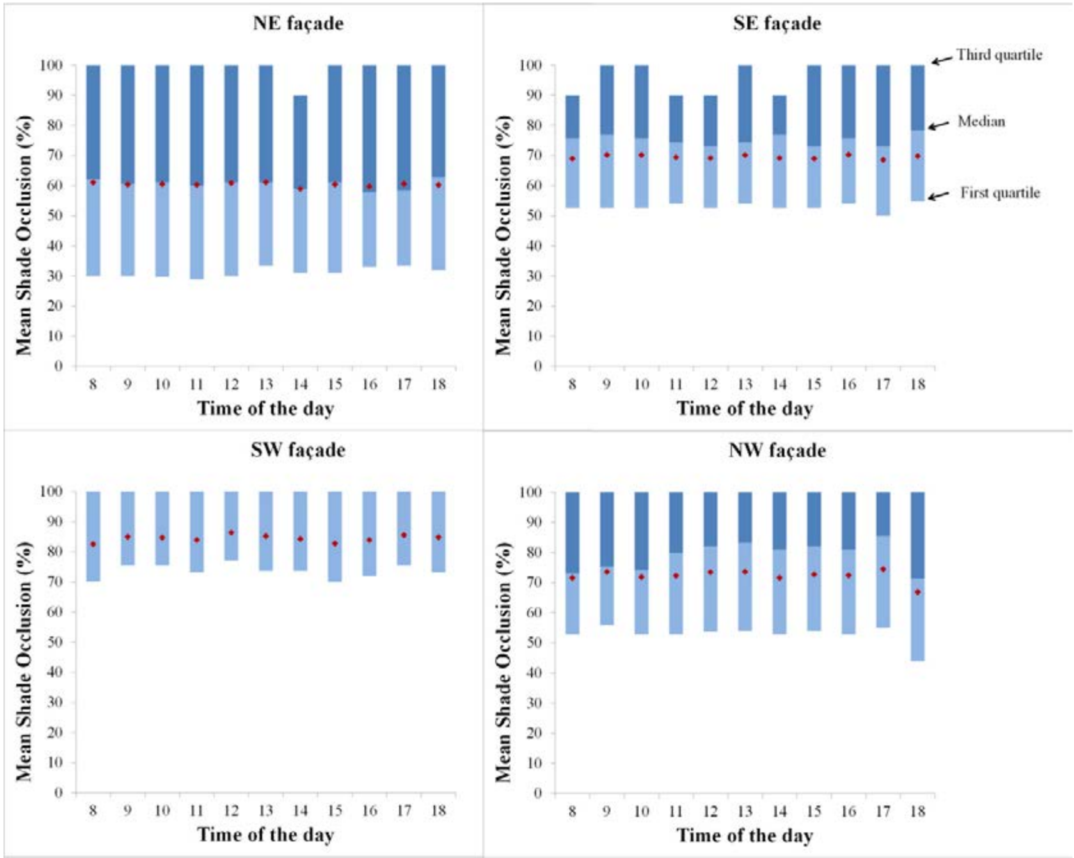
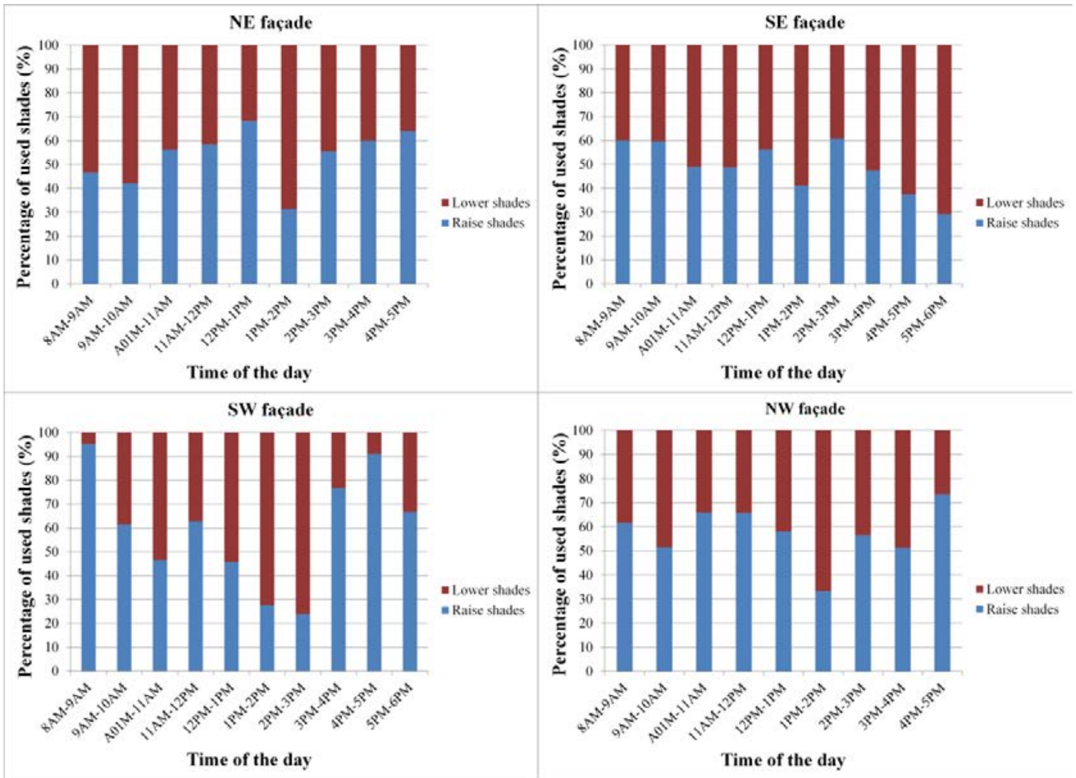

NE façade

SE façade

SW façade

NW façade

*Figure 4 Daily Mean Shade Occlusion for the four façade orientations and averaged for the three days*


NE façade

SE façade

SW façade

NW façade

*Figure 8 Direction of movement between moved shades, for the four façade orientations and averaged for the three days*