

METHODOLOGY FOR QUANTIFYING THE PERFORMANCE IMPLICATIONS OF INTELLIGENT SHADE CONTROL IN EXISTING BUILDINGS IN AN URBAN CONTEXT

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ABSTRACT

This paper presents a high-level overview of a methodology for analyzing window shade use in existing buildings and quantifying the predicted energy use and visual comfort due to occupants' behavior. Time-lapse photography is paired with an image recognition algorithm to facilitate assessment of shade use. The resulting data is directly used in a building performance model to predict energy use and visual comfort under several shade control strategies. The methodology is applied to a commercial office building in downtown Montreal that has over 1200 independently operated shades and is partially shaded by neighboring buildings.

INTRODUCTION

Intelligent control of shading devices in buildings assists in the simultaneous optimization of heating and cooling loads, daylighting, and the improvement of thermal and visual comfort. Tzempelikos and Athienitis (2007) reported a 31% reduction in total secondary energy use (lighting, heating and cooling) when both active lighting and shading control were applied. Using measured data for an experimental office, Lee et al (1998) found cooling and lighting energy reductions of 21% each and a peak cooling load reduction of 13% on a sunny summer day.

Building performance simulation enables the examination of the effectiveness of innovative energy efficiency measures and control strategies. Yet occupant behavior, which can have a significant impact on building performance, has not advanced to nearly the level of detail that heat transfer through building envelopes has, despite the fact that it often has more impact on performance (Hoes, Hensen et al. 2009; Mahdavi and Pröglhof 2009). Enabling detailed occupant behavior models as inputs to building performance simulation has the potential to significantly increase the accuracy of results – both in terms of optimal building design and the corresponding performance. Many studies have found shades to be passively used and in sub-optimal ways (Donn, Selkowitz et al. 2009).

Since the decision-making process of whether an occupant changes a shade position is complex, the traditional approach has been to observe shade use relative to weather conditions and attempt to create correlations (see e.g., Haldi and Robinson, 2009). This approach may be used to generalize results and attempt to apply them to other buildings.

The majority of observational shade control studies fit into one of two categories, including:

- 1) Small-scale (under 50 windows) that measured shade position with sensors over a period of weeks to years (see e.g., Haldi and Robinson, 2009; Reinhart and Voss, 2003)
- 2) Large-scale (up to 700 windows), in which measurements (usually photographic) were typically limited to tens with a sampling frequency of hourly or longer (Rubin, Collins, et al, 1978; Rea, 1984; Inkarojrit, 2005).

The researchers of the small-scale category often acknowledge that the findings are somewhat limited to the specific building that was studied. While these studies may be invasive (to the extent that occupants are aware of the sensors, possibly influencing their behavior), the small sample size enables thorough instrumentation to make other measurements, such as workplane illuminance and occupancy.

For the large-scale category the process of measuring shade positions is cited as a major limitation (Rea, 1984), though the greater sample size results in a higher level of statistical significance. The approach is less suitable for Venetian blinds, for which the slat angle is difficult to determine from photographs. To study shade use, Rea (1984) photographed a building over several days under different weather conditions. He found that manually measuring shade position was tedious and impractical. His approach was to use random sampling to reduce the time for this task. He concluded that while there were some trends in shade use for the different weather conditions and façade orientations, they were not as significant as one might expect (about five percentage points difference in occlusion between different orientations). Rea

presented the results but did not look at the comfort and energy implications of the observed patterns.

Key findings from the major observational studies include (Reinhart and Voss 2003):

- 1) Shade position change frequency is diverse; ranging from never to daily.
- 2) Blind occlusion is higher in south facades than north facades, as people attempt to block direct beam solar radiation.
- 3) Occupants tend to consciously choose a blind position, but it is based on long-term outdoor conditions; diurnal blind position changes are rare.

There are two approaches to using shading device data in building performance simulation, including:

- 1) Direct – the exact measured shade positions are simulated for each window.
- 2) Indirect – a statistical or stochastic model is developed to relate weather conditions to occupant shade use and this, in turn, is simulated.

This paper presents a methodology for automating the process of noninvasively monitoring shading device use in commercial buildings. It focuses on the direct approach, defined above. This methodology is applied to a large commercial building in Montreal, in which approximately 1200 independently controlled shades are studied for a design day. The potential energy savings and visual comfort improvements are predicted for various shade control strategies using EnergyPlus (Crawley, Hand et al. 2008).

METHODOLOGY

The objective of this research was to develop an efficient method for evaluating the potential benefit of implementing automated controlled electric lighting and window shades. By observing current occupant behavior, a realistic baseline is established. While this strategy is best applied on an individual building basis, the conclusions of one study are expected to be applicable to other similar buildings, since the method allows sample sizes to be much larger than previous methods practically permitted. The major steps of the methodology are: 1) photography, 2) photograph pre-processing, 3) image recognition, and 4) building performance model simulation.

Photography

Photography allows the capture of instantaneous shade positions, which can then be processed and converted to a digital database. Photographic vantage points are selected so that the entire façades of interest can be viewed at an angle that is as close as possible to normal to the façade surface.

The sampling rate (photographs per hour) is at the discretion of the user and dependent on the application. The following case study used an hourly sampling rate. This rate is justified by a) the rate of change of the subject was found to be slow, and b) the weather data is hourly, so there is no sense in sampling more frequently than this.

Photograph pre-processing

Each photograph is converted to grayscale to reduce complexity in the image recognition algorithm, as the pixel color variation is transformed into pixel intensity variation (ranging from 0 to 255 or black to white). The pixel coordinates of the corners of each façade are specified manually (though this could be automated in the future). The coordinates are used to perform a projective transform of each photo to an image, such that the windows in the final image are of equal size and all lines are that parallel on the façade are also parallel in the projected image. The transform is performed using MATLAB and demonstrated in Figure 8.

Image Recognition

The custom-built image recognition program sequentially scans each window in each image and attempts to determine its shade position, as illustrated by Figure 9. In this study, MATLAB's image processing toolbox was used to implement the algorithm, but the algorithm does not use built-in functions for finding edges; instead, original low-level code was developed to determine specific features such as the bottom of each shade.

There are three possibilities for shade positions: fully open, fully closed, or partially closed. The last possibility is the easiest to identify, as it characterized as a sudden jump in pixel intensity that is consistent along a horizontal line that spans the window. The software first identifies all partially closed shades; next, it searches each of the remaining shades, which by process of elimination, are either fully open or fully closed. Because there are many instances of significant variation in intensity of the image even for similar objects, the intensity of shades cannot be universally defined. Thus, to determine if a particular shade is fully open or fully closed, the algorithm determines what is likely to be the threshold intensity from the surrounding shades that are partially closed. It searches within a three-window radius and uses a distance weighting (where nearby windows have the greatest influence). This method was found to be effective except for a few cases where a reflection in the building causes abrupt changes in regional brightness. The process is illustrated in Figure 9 and Table 4.

Once the algorithm has predicted the shade position for each window, it assesses the relative certainty of being

correct. Factors that were found to reduce certainty include window cleaning platforms and reflections of background objects such as clouds and buildings, to name a few. For the partially closed shades, the certainty is defined as being proportional to the jump in color between the shaded and non-shaded area for each window. For the fully open or closed shades, the certainty is proportional to the difference in intensity between the mean window intensity and the threshold intensity. The certainty values are then normalized such that the most certain shade receives a value of unity and the rest are relative to that.

For certainty levels below a level (10% was selected for the case study), the image was marked with a green dot, as shown in Figure 8b. This allows manual correction, if desired. The importance of this step is dependent on the application and the predicted error rate. Also, the certainty level threshold could be selected for the application. In the case study, it was selected to minimize the occurrence of false negatives, in favor of false positives.

The measured shade positions for each time step are directly fed into the building performance model, described below.

Building Performance Model Simulation

Building performance simulation is used to translate the shade position data into energy (lighting, cooling, and heating) and visual comfort implications. EnergyPlus was selected for its daylighting and thermal analysis capabilities (Crawley, Hand et al. 2008) and its flat-file structure, which is highly favorable for scripting.

In order to accurately model the daylighting, details about the interior layout of the walls should be specified. Daylighting is highly sensitive to the presence of obstructions and to surface reflectance. An open concept office requires that the perimeter zone be modeled as a single zone. In contrast, a building with closed offices should be modeled using one zone per office. The zone multiplier feature can be used only if each office has equal boundary conditions, operating conditions, geometry, and construction. Since shades can be individually controlled, it is ideal if each office is explicitly modeled. The case study building is open concept, and thus, the remaining description of the model pertains to that configuration. Each zone was sized to be the width of the subject façade, and a depth of 5 meters. The depth was selected as a distance after which the quantity of daylight that penetrates the zone is usually insignificant.

Each perimeter zone – floor-wise and orientation-wise – can be effectively decoupled from the others with minimal error, since they are assumed to be maintained at the same temperature and light cannot pass between stores. Each zone can be simulated independently and

the results can be combined. This has the main advantage of reducing computational time for each simulation and allowing easier tracking of errors.

EnergyPlus has a model for controllable shades, where shades can be in the open or closed state. However, the observed shade use patterns clearly indicate that shades are often neither fully open nor closed. Thus, a method for modeling partial opening is necessary. Each window is discretized into ten window sections of equal size, stacked one on top of another. This allows the shade position to be set open or closed in tenths of the window height. The error in shade position from the discretization is a maximum of 5%, which roughly translates to maximum errors in thermal and daylighting performance of 5%. The one complication that arises is that EnergyPlus would allow any combination of open and closed positions, whereas in order for any of the windows to have a shade in a partially closed position, all shades above it must also be closed (for standard roller shades). Thus, none of the built-in EnergyPlus control algorithms could be applied. For the model, shade positions were controlled by schedule only. Figure 8c shows an example of the output of this analysis. Each window is assigned single variable - shade closure fraction - for each time step.

The “compact schedule” object was used to schedule the shade for each window section. For the baseline case, the data is directly obtained from the image recognition program and converted to shade schedule.

In EnergyPlus, the main output metric of the daylighting analysis is the illuminance at a maximum of two reference points on the workplane or a grid of points in some plane parallel to the floor that has a maximum resolution of 10 by 10. EnergyPlus allows electric lighting to be controlled based on the one or two reference points per zone. Since the shades can be independently controlled in the model (as in reality), workplane illuminance variation is very high (see

Figure 1).



Figure 1: Workplane illuminance indicating high variation (scale in lux) (top) and corresponding shade positions (bottom) (white means shade closed)

Thus, it would be nearly impossible to position the two sensors such that they would be representative of workplane illuminance.

To resolve this, two consecutive simulations are run, in which electric lighting is controlled based on the daylight levels at the grid of up to 100 points (as described below). For the simulation of each zone, two steps were taken, as follows:

- 1) Electric lights are kept off while the daylight distribution is measured using a grid of daylight measurement points as sensors, as shown in Figure 2.

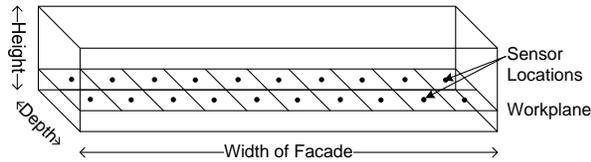


Figure 2: Lighting control zone and illuminance sensor location

- 2) The measured daylight is translated to an electric lighting power schedule, according to equation 1, which indicates dimmable lighting. The simulation is re-run with this electric lighting schedule.

$$P = \begin{cases} P_{electric\,lighting} \cdot \frac{(E_{setpoint} - E_{daylight})}{E_{setpoint}} \cdot A, & P > 0 \\ 0, & P \leq 0 \end{cases} \quad (1)$$

Where P is the electric power for lighting, $P_{electric\,lighting}$ is the lighting power density, $E_{setpoint}$ is the setpoint workplane illuminance, $E_{daylight}$ is the workplane illuminance from daylight alone, and A is the area of the workplane associated with each daylight sensor.

For daylighting controls, each perimeter zone is divided into twenty equally-sized lighting control zones; two deep and ten wide regardless of façade width, as shown in Figure 2. The lighting level in each lighting control zone is controlled based on the illuminance at the center of each rectangular zone at the height of the workplane.

Wall and window constructions are input for the performance model. Only the façade surface is modeled with exterior boundary conditions, while the rest are modeled as adiabatic, since the neighboring interior spaces are assumed to be maintained at the same temperature. Unless measured values are available, operating conditions such as temperature setpoints, internal gains (people and equipment), ventilation, and infiltration can be estimated using typical values for a space of the same type (e.g., commercial offices).

HVAC was modeled as an ideal system, since the focus of this work is on heating, cooling, and lighting loads.

Finally, all external obstructions of significance (i.e. taller than the bottom of the façade and of close proximity) should be modeled. Obstruction geometry for the case study was obtained from Google Earth software (Google 2009). Building heights were determined by measuring the heights of the first floor and multiplying by the number of storeys.

CASE STUDY

A large commercial office building in Montreal was selected as a case study because of its size (translating to a large sample size) and consistent façade construction and shades. Its shades are clearly visible from the exterior under most sky conditions, making it an ideal subject for image recognition. The building is made of two towers of similar height. Façades that face outwards from the building and have simple geometry were selected. They represent approximately one third of the total façade area of the building and are evenly distributed among the four main directions, as indicated by Figure 3 and Table 1.

A tripod-mounted Canon PowerShot A480 was used to take the pictures of each façade at hourly intervals from sunrise to sunset on a clear cold day (Jan 29, 2010). Vantage points were selected to be close to normal to the façade and to avoid reflections, where possible (shown in Figure 3).

The façade dimensions (in pixels and meters) were derived from the knowledge of storey height, window height, and window width (summarized in Table 1).

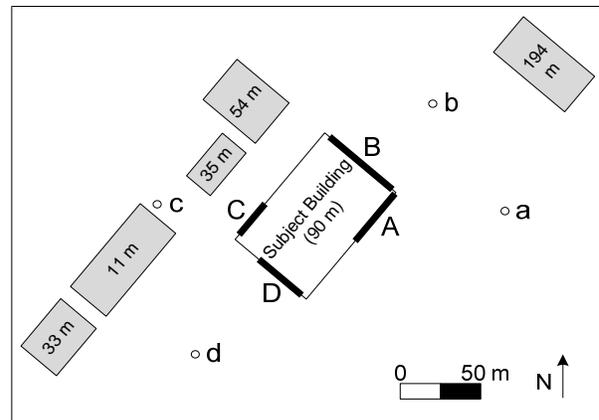


Figure 3: Plane view of building site showing major solar obstructions and the façades that were studied (labeled A through D). Corresponding vantage points are labeled as a through d. Building heights are shown.

The image recognition software was run for all windows. The shade position that the software determined was superimposed on the photographs. Windows for which the shade position was deemed suspect by the code were marked. Most façades had 0 to 10 suspect windows, representing less than 5%. While it may have been possible to fine tune the image recognition software for higher accuracy, it was found that this effort had diminishing returns and that the manual correction of isolated errors was a far better use of time. The results are summarized in Figure 4 to show the high-level trends, while the individual shade positions are accounted for in the final performance

simulation results. Shade positions are assumed to remain constant before and after occupied hours, as indicated by the flat lines. Two major trends can be seen. First, the shades, on average, were lowered by between 13 and 30 percentage points over the (clear) day. Second, the facades with direct solar exposure (A and D) tended to have lower shade positions.

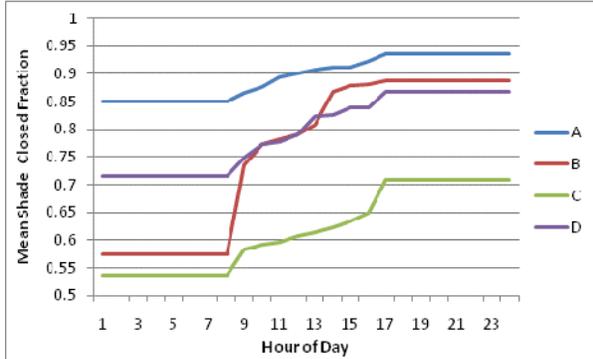


Figure 4: Observed shade use results, averaged over each facade (1 is closed)

Table 1: Summary of case study geometry

Facade	Orientation	Total windows	Number of Storeys
A	S55°E	432	18
B	N35°E	375	15
C	N55°W	216	12
D	S35°W	208	13
-	Total	1231	-

The modeled building properties are summarized in Table 2. Generalized zone geometry and surface reflectances are shown Figure 5.

Table 2: Details about the building envelope and operating conditions

Glazing SHGC	0.271
Glazing Visible Transmittance	0.536
Glazing U-value	1.67 W/m ² K
Shade Transmittance	0.05
Shade Reflectance	0.75
Spandrel thermal resistance	3 m ² K/W
Occupied hours	8:00 – 18:00
Heating setpoint	21°C occupied; 18°C unoccupied
Cooling setpoint	24°C
Installed lighting power density	11 W/m ² (dimnable with power input linearly proportional to light output)
Nominal Lighting Schedule	11 W/m ² (8:00 – 23:00); 3.3 W/m ² (23:00 – 8:00)

Equipment heat gains	8 W/m ²
Occupant heat gains	10 W/m ² (based on 1 person/10 m ²)
Zone dimensions	Façade width by 3.3 m height by 5 m depth
Window to Wall Ratio	0.68

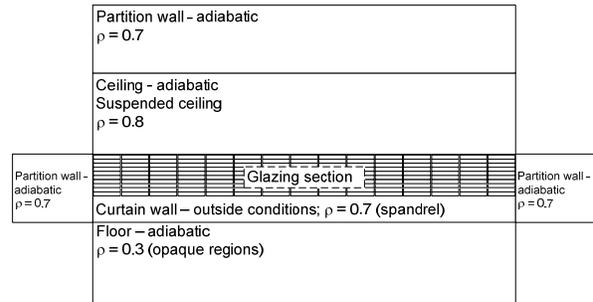


Figure 5: Unfolded view of a single perimeter zone

Next, the MATLAB script for generating input files and running EnergyPlus simulations was sequentially run for each zone. Performance results for the observed shade use patterns were compiled. Next, the control algorithms for motorized shades were defined and implemented into EnergyPlus. The control schemes that were considered are:

- 1) Base case: All lights on (as defined in Table 2); observed manual shade control

Lights dimmed to achieve 500 lux workplace illuminance and:

- 2) Observed manual shade control
- 3) All shades open
- 4) All shades closed
- 5) Shades lowered to level where no beam solar radiation directly enters the glare-free zone, as defined in Figure 6. Shades are completely opened if there is no glare and completely closed during unoccupied hours to decrease heat transfer

These control schemes are referenced herein by their number.

Results

For the case study, the metrics of interest were energy consumption and visual comfort. To determine energy consumption, heating, cooling, and electric lighting loads were considered since they are directly related to shade use patterns. Useful daylight illuminance (UDI) is a scheme that is used to quantify useful daylight (Reinhart, Mardaljevic et al. 2006). The bins are: >100 lux, 100 to 2000 lux, and >2000 lux, with the last being associated with probable discomfort.

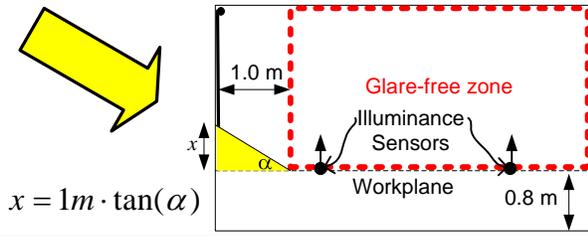


Figure 6: Shade position to prevent direct sunlight from hitting workplane beyond 1 m from the window. α is the solar altitude.

The predicted performance results are shown in Figure 7 and summarized in Table 3.

Some general observations include:

- Controls schemes 3 (shades all open) and 4 (shades all closed) provide lower and upper limits for lighting electricity use.
- Significant discomfort occurs if the southward shades are left in the open position.
- Predicted heating loads in the two northern perimeter zones are two to three times greater than the other two; resulting from lack of solar gains

Table 3: Summary of optimal control strategy by façade for the design day.

Façade	Optimal Control(s)	Comments on optimal control(s)
A (SE)	5	Offers a good compromise between low electric lighting and minimal discomfort
B (NE)	3 or 5	There is no predicted discomfort, so shades should be left open during occupancy
C (NW)	3 or 5	Same as above
D (SW)	2 or 5	Occupants manual control is near optimal; using advanced controls 5 decreases energy use at the cost of some additional discomfort

Generally, the advanced controls scheme (5) performed better or as well as the others. However, the associated cost with such technology would require a substantial improvement, thus likely restricting it to facades with frequent incident beam solar radiation (A and D, in this case).

CONCLUSION

The technique presented provides an innovative means to noninvasively collect vast amounts of data about building occupant behavior with minimal effort relative to previous studies. The data is directly fed to performance simulation where it can be compared to more advanced controls. Applications of this work include:

1. Cost-benefit studies for advanced shade and lighting controls for both new construction and retrofits.
2. Predictive control and load management based on realistic shade use patterns.
3. Statistical shade use models that can be applied to other buildings.

The major contributions of this work include a methodology for:

1. Noninvasively collecting occupant behavior of shade control.
2. Assessing the potential energy savings from implementing controlled lights or shading devices.
3. Directly including observed occupant behavior into building performance simulation.

The results show that the optimal shade control strategy is dependent on orientation. In general, there are trade-offs between energy consumption and comfort. The two major metrics cannot be combined without assigning a monetary value to comfort. The advanced control algorithm that was explored typically offers a good compromise between the two.

Recommendations for Application

This paper presented a high-level overview of a relatively complex process. The work will be published in a series of more detailed papers in the future and will include the image recognition software, which will be subsequently made public.

For the photography aspect of this task, the authors recommend setting up a quasi-permanent camera with automatic image capturing. The manual process of photography is admittedly tedious; though no more so than the cited works, which also required the manual interpretation of images (unlike this method).

The case study focused on a building with relatively clear windows and on a clear day, which was found to be the most straightforward and least erroneous for image recognition. However, the algorithm could be extended to more complex situations (e.g., temporarily irregular weather and geometry, and tinted windows). In general, any feature detectable to the human eye can be programmed to be detected with software. A methodology for removing reflections as part of post-processing is currently being considered. As previously noted, as with the automation of any process, each step should be selected to be either manual or automatic in an attempt to reduce overall long-term effort.

Future Work

In the future, observation periods should be extended to weeks or months to properly characterize the long-term patterns of shade use. The study should also be

extended to include observations for representative days for each season of the year. Cooling loads will play a major role in summertime performance. The technique of discretizing windows affects air exchange with the cavity behind the shade and thermal bridging from window frames. A new shade model for partially closed shades would resolve this.

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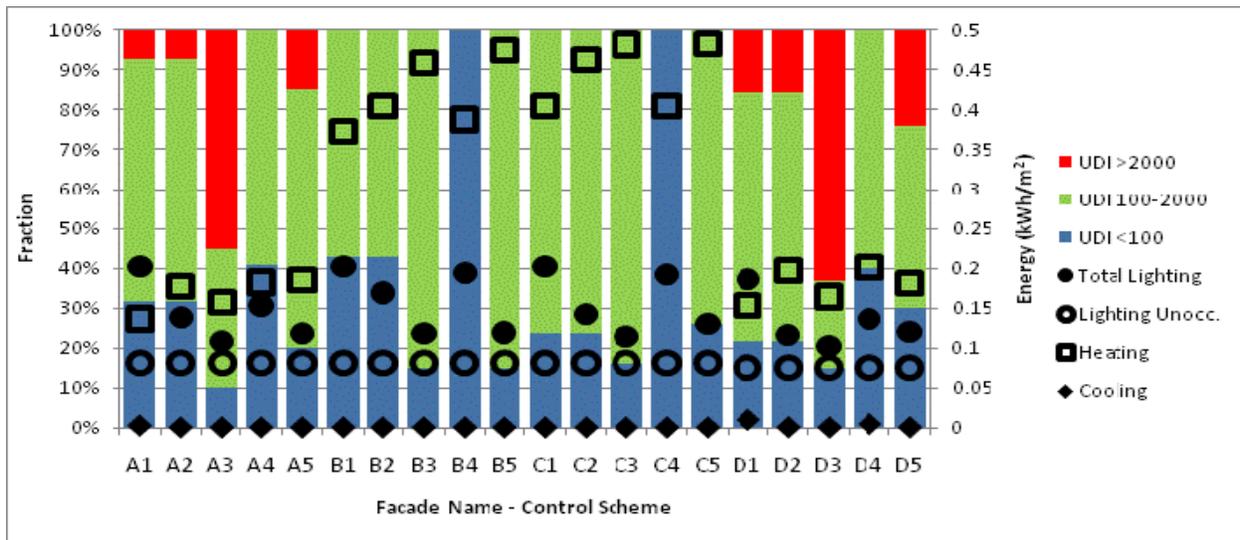


Figure 7: Predicted performance for each of the facades under the five different control schemes. The horizontal labels indicate façade letter and control scheme number.

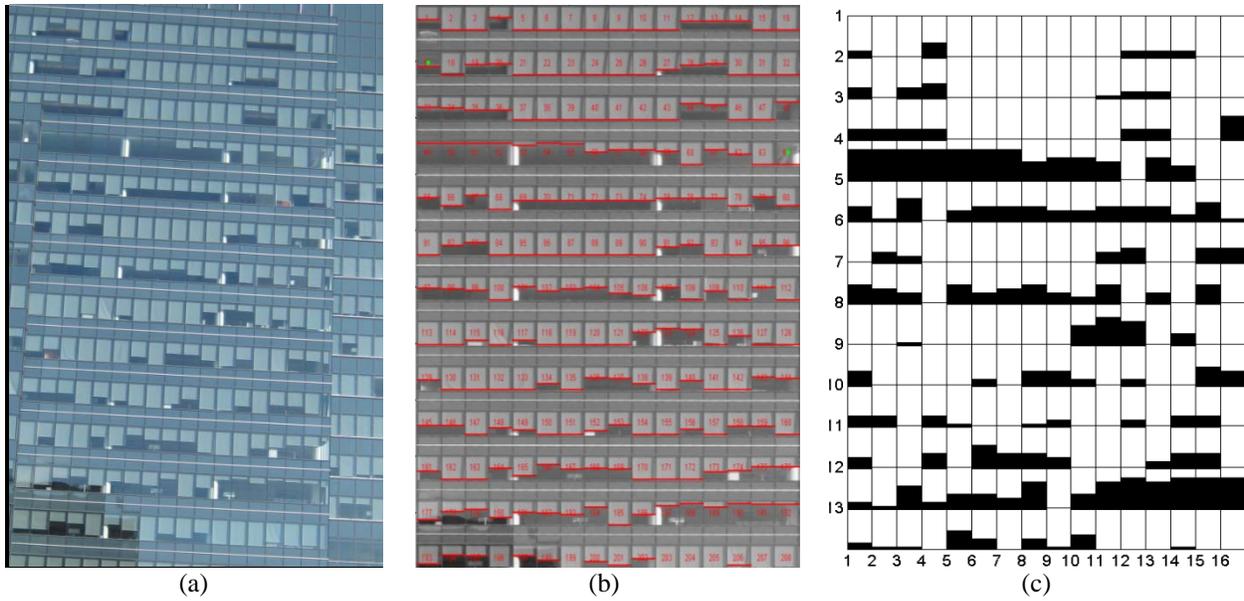


Figure 8: Sample of image processing algorithm results. (a) original photograph; (b) after cropping, transforming, and shade position identification algorithm (note: the low-certainly predictions – two, in this case - are marked with dots), (c) plot of open/closed (black/white) state for each shade for each window section (with discretization scheme in tenths of a window height). A daily shade schedule is made up of an three-dimensional array that stores this information for each daylight hour.

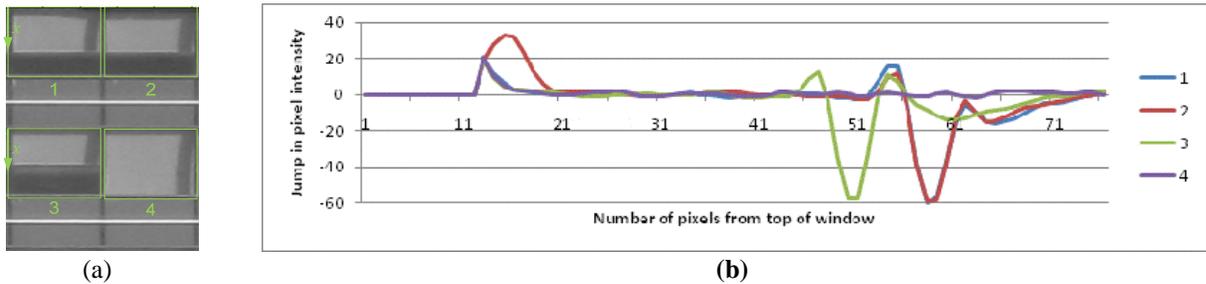


Figure 9: (a) sample image of four typical windows, (b) jump in pixel intensity from top to bottom of each window. Since shaded areas are lighter than the non-shade areas, the minimum value in the jump is the most probably the shade bottom. Any minimum jump in intensities of above -5 are deemed to be too small to indicate the bottom of a shade.

Table 4: Intensities and thresholds for all partially closed shades corresponding to Figure 9. Since this sample only has four windows and three of them have partially closed shades these three set the threshold intensity for determining if the shade in window 4 is fully closed or open. Since the mean intensity of window 4 is much higher than the threshold, the shade in window 4 is predicted to be closed. With this high of a margin (about 25 points of intensity), a relatively high certainty value is assigned and it is unlikely to be deemed suspect.

Window Number	Mean window intensity	Mean shade color	Mean non-shade color	Threshold intensity	Distance to shade of interest
1	122.1	146.6	82.7	114.7	1.4
2	117.3	141.9	81.1	111.5	1.0
3	121.3	148.6	92.2	120.4	1.0
4	148.3	(neither fully open or fully closed)			