The impact of daylight fluctuation on a daylight dimming control system in a small office

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Abstract

The variation of daylight under clear and partly cloudy sky conditions was analyzed to examine the fluctuation of electric light controlled by a daylight dimming control system. Field measurements were performed in a full-scale mock-up office space that faced south. Horizontal and 35° blind angle conditions were tested. Three different shielding conditions for a photosensor were examined to predict the fluctuation of electric lights.

The fluctuation of vertical illuminance under partly cloudy sky conditions was 23.8 times as greater than that under the clear sky conditions. A multiple linear regression model was employed to determine the fluctuation range of outdoor daylight illuminance according to sun positions under partly cloudy sky conditions. The fluctuation of electric light output under clear sky conditions was less than 6.6% of target illuminance. In contrast, it varied greater than 50% of target illuminance under the partly cloudy sky conditions. Shielding condition effectively blocked the direct influence of daylight fluctuation on photosensor. The linear correlation between the fluctuation of outdoor vertical illuminance and photosensor illuminance was the weakest when the photosensor was partially-shielded. From this, it was found that partial shielding of photosensors is a desirable strategy for reducing the fluctuation of light output from electric lights integrated with daylight dimming systems.

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1. Introduction

A variety of control alternatives have been suggested to reduce lighting energy consumption. Among them, daylight dimming control systems are considered to save lighting energy most effectively since they use daylight as an alternative light source. It is known that approximately 20–40% of lighting energy consumption in buildings can be reduced by using daylight dimming control systems [1]. However, daylight dimming systems have not been widely applied to buildings due to the visual problems associated with fluctuating electric light outputs under varying sky and cloud conditions [2].

The most significant problem is the fluctuation of illuminance levels, which can cause visual annoyance to occupants. The dimming control systems that cause frequent fluctuation of light were often deactivated by building users, resulting in the loss of investment [3]. The fluctuation occurs since the systems control light output from lighting fixtures based on daylight levels, which vary according to sky conditions. Especially, the fluctuation becomes more significant under partly cloudy days. In addition, the fluctuation of electric light output is sensitively influenced by the way photosensors are shielded and positioned. In order to effectively utilize the daylight dimming control system, the visual problems associated with illuminance fluctuation due to daylight and electric light should be addressed.

2. Method

This study examines the effect of daylight fluctuation on the variation of illuminance controlled by a daylight dimming system. Field measurements were performed in a full-scale mock-up office space where a dimming control system was installed.

2.1. Test space

The full-scale mock-up office space used in this study was located in Ann Arbor, MI, USA (latitude: 42°14'; longitude:
It was located on the second floor of a three-story building and faced directly south. Its dimensions were 3 m × 4.2 m × 2.85 m (10 ft × 14 ft × 9.5 ft). There were no obstructing buildings in front of the window. Several trees stood 9 m (30 ft) away from the south façade of the buildings, which cast shadow on it. The ground in front of the south façade was covered with grass.

The space was furnished for typical private office use. The ceiling had 0.6 m × 0.6 m (2 ft × 2 ft) suspended ceiling grids. The floor was finished with wood. Wall surfaces were finished with wall papers with light beige color. A desk and chair were placed, and a personal notebook computer with 16.1 in. of TFT screen was located at the centerline of the space. A 1.5 m (5 ft) high plant was placed near the window, but it did not block the daylight from the window to desktop.

A 1.42 m × 2.02 m (4.75 ft × 6.75 ft) window was installed on the south wall. The window was glazed with single pane clear glass with 79% of light transmittance. The reflectance of ceiling, walls and floor were 75%, 60%, and 30%, respectively. A Venetian blind with 1 in. gap between each slat was installed on the windows.

The dimensions of a desk were 1.5 m × 0.75 m × 0.75 m (5 ft × 2.5 ft × 2.5 ft). Its geometric center was located at the centerline of the space. The distance between the window and the geometric center of the desktop was 16.51 m (6.5 ft). The reflectance of desk surface was 27%. The detailed dimensions of the room are shown in Fig. 1.

2.2. Lighting fixture and daylight dimming control system

The lighting fixture used in this study was a recessed 0.6 m × 0.6 m (2 ft × 2 ft) parabolic fluorescent troffer with 7.62 cm (3 in.) louvers. Two T8 ‘U’ shaped lamps and 3 × 3 arrays of cells were applied to the luminaire. They consumed 56 W, and the efficiency of lighting fixture was 59%. The fixture generated the maximum 1236 cd toward the nadir. The target illuminance level on the desktop provided by the fixtures was 750 lx.

The fixtures were controlled by a daylight dimming system manufactured by the ‘L’ company. The photosensor was located at the center of the ceiling aiming directly downward. It was located according to the installation guidelines by the manufacturer [4]. The location of the photosensor in the room is shown in Fig. 1.

The ECO-10 electronic fluorescent dimming ballast installed on the fixture provided dimming ranges between 10% and 100%. The light output was controlled according to the signal generated by a controller manufactured by the ‘L’ company. The controller was capable of controlling the electric light output from the lighting fixtures according to the input signals from the photosensor and its control settings.

Before the initiation of data monitoring procedure, all possible dimming control algorithms were examined according to the control setting of the controller. Among them, the control setting with medium sensitivity was selected to control electric light output. The setting had the maximum light output when photosensor illuminance was less than 35 lx (3.25 fc), and the minimum light output when the illuminance at the photosensor was greater than 395 lx (36.8 fc). The linear dimming algorithm used in this study is shown in Fig. 2. This algorithm was used to analyze the fluctuation of light output from lighting fixture.

2.3. Data monitoring

Photometric sensors and irradiance sensors manufactured by LI-COR were used for the monitoring of illuminance and irradiance. They detected illuminance and irradiance in currents and converted into standard units using calibration constants assigned for them. The sensitivity of the photometric sensor was typically 20 mA/100 klx, and the maximum deviation of linearity was 1% up to 100 klx [5].

An automatically equipped data monitoring system manufactured by Campbell Scientific, Inc. was used for data recording. The system detected the signals in voltages ranging from −5 V to +5 V. Its accuracy range is from −2.5 mV to 2.5 mV when temperature is between 0 °C and 40 °C.
execution interval for each channel can be up to 250 ms at 100 Hz [6].

Since the photometric and irradiance sensors generated signals in currents and the data logger detected signals in voltages, resistances manufactured by LI-COR were installed between each sensor and channel of data logger in order to covert the signals into voltage.

A specific computer program was developed to manipulate the data logger system. The program converted the monitored voltages into standard units using calibration constants assigned for the sensors. It also controlled the data logging process such as the execution period for data monitoring.

The illuminance levels at 15 points and the irradiance level at 1 point were measured. Two sensors were assigned for the monitoring of outdoor horizontal and vertical illuminances. Outdoor horizontal irradiance was also measured. Five sensors were placed for the monitoring of indoor horizontal illuminance. They were positioned starting from 0.3 m (1 ft) away from the window. Their height was 0.75 m (2.5 ft) from the floor surface. Three of them were placed on the desktop. Indoor vertical illuminance levels at the center of each wall surface were measured. The illuminance levels on a computer screen and at the position of the viewer’s eye were monitored.

Three photometric sensors were positioned at the center of the ceiling in order to monitor the daylight illuminance according to shielding conditions when the daylight dimming control system was turned off. Partial shielding, full shielding and no shielding conditions were applied to the three photometric sensors as they were applied to the photosensor connected to the control system.

The field view of the photometric sensor was restricted by the shielding conditions. The fully-shielded condition showed 67.2° aperture which had 33.6° half angle of a field view. The partially-shielded photometric sensor was shielded from the window but open to the rear area of the room. The partially-shielded condition blocked half of the field view of the photosensor. The reflectance of the inside of the shielding material was 75%. Detailed description of shielding conditions applied to the photometric sensors is shown in Fig. 3.

The blind control conditions were no blinds (unobstructed clear glazing), horizontal blinds oriented at 0°, and 35° applying the reflectance of 83% for the blind slats. The data monitoring were performed from April 1, 2003 to August 31, 2003. The daily monitoring periods were from 07:00 to 20:00. The monitoring intervals were 1 min and 5 min.

3. Results

The illuminance fluctuation was defined as the difference in illuminances at two moments of measurement. In order to examine the influence of sky conditions on, the monitored data were classified into two categories; clear sky and partly cloudy sky conditions. The classification was based on the ratio of diffuse solar radiation to global solar radiation, which was recommendation by the Illuminating Engineering Society of North America (IESNA) [7]. For a clear sky day, the ratio is less than 0.3. For a partly cloudy sky condition, the ratio ranges from 0.3 to 0.8.

3.1. Fluctuation of outdoor daylight illuminance

Overall, the fluctuation of vertical and horizontal illuminance under partly cloudy sky was much significant compared to the fluctuation under clear sky conditions. In particular, the fluctuation of vertical illuminance under partly cloudy sky conditions was 23.8 times greater than the fluctuation under the clear sky condition.

It appears that the photosensor signal in the space was significantly influenced under the partly cloudy sky conditions, and the light output from lighting fixtures fluctuates within a great range. Approximately 51.1% of fluctuation in vertical illuminance was between 2000 lx and 5000 lx. The frequency analysis for the fluctuation of outdoor illuminance is shown in Table 1. More detailed frequency analysis for the vertical...
illuminance under partly cloudy sky conditions is shown in Table 2.

The variation patterns of outdoor illuminance for a clear and partly cloudy sky conditions are shown in Figs. 4 and 5. Outdoor daylight illuminance under clear sky conditions increased constantly as the altitude of the sun increased. The illuminance on the south façade of building is strongly influenced by the sun position. The outdoor horizontal and vertical illuminance levels show a very stable changing pattern for all day except on several occasions in the morning.

Under partly cloudy sky day conditions, the sun is frequently blocked by clouds. Due to this reason, outdoor daylight level changes suddenly and becomes unstable. The altitude and azimuth of the sun did not strongly influence the daylight levels as they did under clear sky conditions. During the time when the sun was on the south, the daylight level did not reach the maximum value since the sun was blocked by clouds. This indicates that outdoor daylight levels do not correlate with the position of the sun when the sun was blocked by clouds under a cloudy sky day condition. The daylight levels frequently fluctuated due to the effect of clouds. When the sun is exactly due south, the daylight illuminance is the highest if the sun is not blocked by the clouds. However, once the clouds block the sun and release it, the change of daylight levels becomes pronounced. Daylight illuminance under partly cloudy sky conditions are not strongly correlated to the sun position compared to clear sky conditions. The conditions of cloud are more critical factors to the fluctuation of daylight illuminance.

### 3.2. Prediction for the fluctuation of outdoor daylight illuminance

Multiple linear regression was used to develop the prediction model for the fluctuation of outdoor daylight illuminance level under partly cloudy sky conditions. For the monitored illuminance data, the absolute value of fluctuation range in outdoor vertical illuminance level was considered to be the dependent variable. This was because indoor daylight illuminance is significantly influenced by the outdoor vertical illuminance that arrives at a window surface. The fluctuation range was determined by subtracting the former illuminance from the latter illuminance from the latter illuminance between the consecutively monitored illuminance data.

The altitude and azimuth of the sun were considered to be independent variables in the prediction model. In this study, the altitude and azimuth before noon were equal to those in afternoon, since the data monitoring was performed in a
south-facing space. The azimuth ranged from $-100^\circ$ to $100^\circ$ and the altitude varied from $0^\circ$ to $72^\circ$. The influence of the area and density of clouds on the fluctuation was not considered in the prediction model.

In order to develop the prediction model for partly cloudy sky conditions, the illuminance change patterns were categorized according to the fluctuation range. The data representing partly cloudy sky conditions were divided separately so that they could be used for multiple regression models.

First, scatter plots were prepared to diagnose what type of relationship existed between the independent and dependent variables. It seemed that the relationship could be explained by a polynomial function rather than linear function. Hence, a standard second degree polynomial regression model was selected using altitude and azimuth. The model is expressed as follows:

$$ Y = b_0 + b_1(\Theta) + b_2(\Theta)^2 + b_3(\alpha) + b_4(\alpha)^2 + b_5(\Theta)(\alpha) + \epsilon_0 $$

where $Y$ is the fluctuation range of outdoor vertical daylight illuminance [lx]; $\Theta$ the altitude [degrees]; $\alpha$ the azimuth [degrees].

It appeared that the plot between altitude and daylight illuminance fluctuation had unequal error variances since the plot showed a prototype of regression patterns where the error variances increase with independent variable. Therefore, it was necessary to perform a transformation on the dependent variable. It was expected that the transformation will result in higher correlation, and the variability of fluctuation level at different altitude will be constant. According to the prototype regression pattern, the logarithmic transformation was used. The transformation is expressed as follows:

$$ Y' = \log_{10} Y $$

where $Y$ is the originally calculated fluctuation range of vertical daylight illuminance [lx]; $Y'$ is the transformed fluctuation range of vertical daylight illuminance [lx].

Next, a scatter plot between independent variables and the transformed fluctuation range ($Y'$) was prepared. After it was confirmed that a polynomial relationship existed between them, a multiple regression model for the fluctuation of daylight illuminance was developed using SPSS (Statistical Package for Social Science). The model was tested with a significant level of 0.05 to examine whether it was acceptable.

Finally, the significance level for each independent variable in the prediction model was examined to assess whether all independent variables were significant contributors to the fluctuation range of the illuminance. The interaction between altitude and azimuth was also examined. The results indicated that altitude and azimuth were critical contributors, but no interaction existed between them ($t = 0.02, p > 0.05$). Therefore, the prediction model was adapted excluding the interaction between altitude and azimuth.

The scatter plots between the transformed daylight fluctuation and altitude, and azimuth are in Figs. 6 and 7. The final regression model should be expressed in terms of original fluctuation range of vertical daylight illuminance ($Y$), since transformation was used. Using antilog, the prediction model is expressed as follows:

Original fluctuation range

$$ = \text{antilog} [1.1652 + 0.1136(\Theta) - 0.0011(\Theta)^2 - 0.0003(\alpha) - 0.0001(\alpha)^2] $$

The ANOVA analysis results performed in this study indicated that the altitude ($t = 14.44, p < 0.05$) and azimuth ($t = -1.43, p < 0.05$) were important contributors to the fluctuation range of outdoor vertical daylight illuminance. Although the coefficients for each parameter were not great, the prediction model was acceptable within 5% of significance level. The ANOVA analysis result indicated that linear relationship existed between the fluctuation range of outdoor vertical daylight illuminance and altitude, and azimuth, $F (2, 1712) = 354.79, p < 0.05$.

However, the coefficient of determination for the model was not very high ($r^2 = 0.453$). It appears that this low correlation occurred because the daylight illuminance levels showed greater or smaller fluctuation ranges under partly cloudy sky.
days, although the altitude and azimuth varied steadily during the data monitoring period.

In general, the outdoor daylight illuminance under a clear sky condition increases as the altitude of the sun increases. If clouds block the sun and release it again when the altitude was high, the fluctuation range of daylight illuminance becomes greater. On the other hand, the fluctuation range is small if the sun is blocked and released at lower altitude conditions. In this research, the full-scale mock-up test place was facing south. Therefore, the fluctuation range was very wide when the sun was blocked by the clouds at higher altitude conditions.

The other factor that influenced the outdoor daylight illuminance was the conditions of clouds, for example, the area, thickness and density of clouds in the sky. Under the same altitude condition, the fluctuation range of daylight illuminance might be very low or significantly great according to the conditions of clouds. Although the effect of cloud condition was not considered in the model, the data used for the prediction model indicated that the fluctuation range was significantly affected by the presence of clouds when the altitude was high.

3.3. Illuminance fluctuation at photosensors and workplane

The fluctuation of illuminance under a partly cloudy sky conditions were significantly greater than that of clear sky conditions. Under clear sky conditions, it appears that the blind angle was not an important factor to the fluctuation of photosensor illuminance and the electric light output from lighting fixture.

The mean value of fluctuation on workplane was within 3.87 lx, which is very small. The fluctuation at photosensors did not show significant difference according to the shielding conditions. The difference in fluctuation was less than 3 lx for all shielding conditions when the blinds were angled. The photosensor illuminance fluctuated within 3.44 lx when the unshielded condition was used.

The electric light output from lighting fixture can be controlled stably under a clear sky day regardless of the shielding conditions, since the variation of photosensor illuminance was not strongly influenced by the stable change of daylight.

Under partly cloudy sky conditions, the blind angle was not an important factor in the fluctuation of illuminance, since the fluctuation did not show significant differences according to the blind angles. However, the shielding conditions were effective contributors to preventing high fluctuation of photosensor illuminance.

The unshielded conditions seem to be significantly influenced by the change outdoor illuminance. However, the two shielded conditions effectively reduced the fluctuation under partly cloudy sky conditions. In particular, the mean value of fluctuation at the photosensors showed a difference up to 38.76 lx when the unshielded and partially-shielded conditions were used.

The fluctuation caused by partially-shielded and full-shielded conditions did not show significant difference. The electric light output would be stably controlled without significant fluctuation when shielding conditions were applied to photosensors. A summary of illuminance fluctuation at photosensors and workplane is shown Table 3. Frequency analysis for the fluctuation is shown in Tables 4–7.

3.4. Correlation analysis

The fluctuation of illuminance at photosensors and desktop is significantly influenced by the variation of outdoor daylight illuminance. In particular, the fluctuation of illuminance at photosensor is a very critical factor in controlling the electric light output from lighting fixtures.

In this study, linear prediction models were developed to determine the relationship between the fluctuation of outdoor vertical illuminance and the variation of illuminance at photosensors and desktop under partly cloudy sky conditions. The prediction models used the method of least squares that
The models were tested with a significant level of 5% to examine whether they were acceptable. For all cases, the test results indicated that the linear prediction models were acceptable. The coefficients of determination ($r^2$) of the models were greater than 0.88 for horizontal and 35° blind conditions. It means that the variation in mean response for the overall illuminance fluctuation at photosensors and desktop was reduced more than 88%, when the outdoor vertical illuminance was considered in the prediction models. The detailed regression and test results are in Table 8.

Table 4
Frequency analysis for the fluctuation of daylight illuminance (clear sky, horizontal blind)

<table>
<thead>
<tr>
<th>Fluctuation range [lx]</th>
<th>Desktop Unshielded</th>
<th>Partially-shielded</th>
<th>Fully-shielded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency [%]</td>
<td>Frequency [%]</td>
<td>Frequency [%]</td>
</tr>
<tr>
<td>&lt;50</td>
<td>6258 100</td>
<td>6258 100</td>
<td>6258 100</td>
</tr>
<tr>
<td>Total</td>
<td>6258 100</td>
<td>6258 100</td>
<td>6258 100</td>
</tr>
</tbody>
</table>

Table 5
Frequency analysis for the fluctuation of daylight illuminance (clear sky, 35° blind)

<table>
<thead>
<tr>
<th>Fluctuation range [lx]</th>
<th>Desktop Unshielded</th>
<th>Partially-shielded</th>
<th>Fully-shielded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency [%]</td>
<td>Frequency [%]</td>
<td>Frequency [%]</td>
</tr>
<tr>
<td>&lt;50</td>
<td>4870 99.98</td>
<td>4874 99.96</td>
<td>4876 100</td>
</tr>
<tr>
<td>51–100</td>
<td>6 0.12</td>
<td>2 0.04</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4876 100</td>
<td>4876 100</td>
<td>4876 100</td>
</tr>
</tbody>
</table>

Table 6
Frequency analysis for the fluctuation of daylight illuminance (partly cloudy sky, horizontal blind)

<table>
<thead>
<tr>
<th>Fluctuation range [lx]</th>
<th>Desktop Unshielded</th>
<th>Partially-shielded</th>
<th>Fully-shielded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency [%]</td>
<td>Frequency [%]</td>
<td>Frequency [%]</td>
</tr>
<tr>
<td>&lt;50</td>
<td>609 62.98</td>
<td>648 67.01</td>
<td>662 92.98</td>
</tr>
<tr>
<td>51–100</td>
<td>173 17.89</td>
<td>148 15.31</td>
<td>42 5.90</td>
</tr>
<tr>
<td>101–150</td>
<td>81 8.38</td>
<td>77 7.96</td>
<td>8 1.12</td>
</tr>
<tr>
<td>151–200</td>
<td>41 4.24</td>
<td>47 4.86</td>
<td>13 1.83</td>
</tr>
<tr>
<td>201–250</td>
<td>18 1.86</td>
<td>23 2.38</td>
<td>2 0.28</td>
</tr>
<tr>
<td>251–300</td>
<td>20 2.07</td>
<td>9 0.93</td>
<td></td>
</tr>
<tr>
<td>301–350</td>
<td>10 1.03</td>
<td>5 0.52</td>
<td></td>
</tr>
<tr>
<td>351–400</td>
<td>5 0.52</td>
<td>8 0.83</td>
<td></td>
</tr>
<tr>
<td>401–450</td>
<td>5 0.52</td>
<td>2 0.21</td>
<td></td>
</tr>
<tr>
<td>451–500</td>
<td>5 0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>967 100</td>
<td>967 100</td>
<td>712 100</td>
</tr>
</tbody>
</table>

Table 7
Frequency analysis for the fluctuation of daylight illuminance (partly cloudy sky, 35° blind)

<table>
<thead>
<tr>
<th>Fluctuation range [lx]</th>
<th>Desktop Unshielded</th>
<th>Partially-shielded</th>
<th>Fully-shielded</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency [%]</td>
<td>Frequency [%]</td>
<td>Frequency [%]</td>
</tr>
<tr>
<td>&lt;50</td>
<td>479 64.99</td>
<td>487 66.08</td>
<td>534 93.03</td>
</tr>
<tr>
<td>51–100</td>
<td>125 16.96</td>
<td>119 16.15</td>
<td>40 6.97</td>
</tr>
<tr>
<td>101–150</td>
<td>58 7.87</td>
<td>73 9.91</td>
<td>6 1.05</td>
</tr>
<tr>
<td>151–200</td>
<td>39 5.29</td>
<td>44 5.97</td>
<td></td>
</tr>
<tr>
<td>201–250</td>
<td>31 4.21</td>
<td>14 1.90</td>
<td></td>
</tr>
<tr>
<td>251–300</td>
<td>5 0.68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>737 100</td>
<td>737 100</td>
<td>574 100</td>
</tr>
</tbody>
</table>

minimizes the error sum of square (SSE) between the two variables.
system. The unshielded condition would cause a wide range of illuminance fluctuation on desktop when the fluctuation range of outdoor illuminance was great.

However, the fluctuation of illuminance was less influenced by the variation of outdoor vertical illuminance when a partially-shielded condition was used. This study recommends that the partially-shielded photosensor condition can be effectively applied to minimize the fluctuation of light output from lighting fixture.

It is interesting that the correlation for a fully-shielded condition was lower than that of partially-shielded condition. The difference ranged from 0.032 to 0.046. This result occurred due to difference of viewing angle caused by the shielding conditions. The fully-shielded photosensor detected the change of illuminance on desktop which was significantly influenced by the variation of outdoor illuminance. However, the partially-shielded photosensor was shielded from the window but open to the rear area of the room. Due to this configuration, the photosensor detected the reflected light from the back wall and rear part of the sidewall which was less significantly influenced than the variation of illuminance on desktop area.

### 3.5. Prediction of fluctuation of electric light output

The fluctuation of electric light output was predicted using linear regression models. They were developed under partly-cloudy sky conditions since outdoor illuminance did not significantly fluctuate under clear sky conditions. Three photosensor shielding conditions and two blind angles were considered in the models. A significant level of 5% was used to determine the acceptability of the models.

The fluctuation of electric light output was influenced by blind angles and the variation of outdoor vertical illuminance. The fluctuation range of light output under horizontal blind conditions is greater than that under a 35° blind condition. The difference in fluctuation was approximately 10%. The electric light output was more easily influenced by the change of outdoor vertical illuminance, since the horizontal blind angle had more wide area of opening between blind slats than 35° blind.

Photosensor shielding conditions were a significant factor to the fluctuation of light output. They significantly reduced the fluctuation. Overall, the unshielded photosensor condition caused the greatest fluctuation range. When the horizontal blind was used, the unshielded condition showed up to 90% of fluctuation in light output. The partially-shielded photosensor caused the least variation of light output. The maximum fluctuation was less than 23% of total light output when the change of outdoor vertical illuminance was 47,543 lx.

Below 5000 lx of change in outdoor vertical illuminance, the light output was not significantly influenced by the shielding conditions. As the change of outdoor vertical illuminance became greater than 10,000 lx, the shielding conditions effectively reduced the fluctuation of light output. The

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### Table 8

Correlation between the fluctuation of outdoor vertical daylight illuminance and the variation of illuminance at photosensors and desktop

<table>
<thead>
<tr>
<th>Blind</th>
<th>Fluctuation of daylight illuminance</th>
<th>Prediction model</th>
<th>$r^2$</th>
<th>$F$</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>35°</td>
<td>Desktop</td>
<td>$Y = 0.007 \text{OVF} - 5.164$</td>
<td>0.943</td>
<td>12,030.8</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Unshielded</td>
<td>$Y = 0.006 \text{OVF} - 2.076$</td>
<td>0.939</td>
<td>11,098.9</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Partially-shielded</td>
<td>$Y = 0.002 \text{OVF} - 1.638$</td>
<td>0.88</td>
<td>4121.13</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Fully-shielded</td>
<td>$Y = 0.003 \text{OVF} - 2.484$</td>
<td>0.926</td>
<td>6998.7</td>
<td>0.00</td>
</tr>
<tr>
<td>Horizontal blind</td>
<td>Desktop</td>
<td>$Y = 0.009 \text{OVF} - 10.067$</td>
<td>0.923</td>
<td>11,278.2</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Unshielded</td>
<td>$Y = 0.008 \text{OVF} - 8.620$</td>
<td>0.939</td>
<td>14,406.24</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Partially-shielded</td>
<td>$Y = 0.002 \text{OVF} - 1.370$</td>
<td>0.891</td>
<td>5673.7</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Fully-shielded</td>
<td>$Y = 0.004 \text{OVF} - 4.804$</td>
<td>0.913</td>
<td>7304.1</td>
<td>0.00</td>
</tr>
</tbody>
</table>

OVF: fluctuation of outdoor vertical daylight illuminance [lx].

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Fig. 8. Relationship between the fluctuation of electric light output and outdoor vertical illuminance fluctuation (partly cloudy sky, 35° blind).

Fig. 9. Relationship between the fluctuation of electric light output and outdoor vertical illuminance fluctuation (partly cloudy sky, horizontal blind).
difference in light output caused by unshielded and the two shielded conditions became greater as the outdoor vertical illuminance increased. The relationship between the fluctuation of outdoor vertical illuminance and the variation of electric light output are shown in Figs. 8 and 9.

The coefficient of determination ($r^2$) of the models shown in Table 9 was the lowest for partially-shielded photosensor. It means that the fluctuation of light output was less influenced by the change of outdoor vertical illuminance when the partially-shielded photosensor was used.

The test results for the prediction models indicated that the models were acceptable under the significance level of 0.05. The test results are in Table 9.

### 4. Conclusions

Field measurements were performed for a small office space under various daylight conditions. The fluctuation of illuminance and electric light output were examined according to photosensor shielding conditions and blind angles. Using a multiple linear regression method, a prediction model for the fluctuation of outdoor vertical illuminance was developed to predict the variation of illuminance under a partly cloudy sky. A summary of general findings of this study is as follows:

1. The fluctuation of illuminance under partly cloudy sky was much significant compared to the fluctuation under the clear sky. The fluctuation of vertical illuminance under the partly cloudy sky condition was 23.8 times as greater as the fluctuation under the clear sky condition.
2. Multiple linear regression models developed to predict the variation of outdoor illuminance indicate that the altitude and azimuth were important contributors to the fluctuation range of outdoor vertical daylight illuminance under partly cloudy sky conditions. The fluctuation range was very wide when the sun was blocked by the clouds at higher altitude conditions. However, the range was small when the sun was blocked and released at lower altitude conditions. This result implies that the daylight dimming control system should be more carefully applied to achieve stable variation of light when solar altitude is high under partly cloudy sky conditions.
3. A daylight dimming control system under a clear sky day condition would not cause significant fluctuation in light level, since the fluctuation range of photosensor illuminance was very stable and narrow. The photosensors detected narrow change range of illuminance and the daylight dimming control system illuminated the desktop with a low change ranges.
4. The daylight dimming control system should be carefully used under a partly cloudy sky. Under the partly cloudy sky conditions, the photosensor signal in the space was so significantly influenced by the fluctuation of daylight illuminance that the light output from lighting fixtures would vary within a large range. Accordingly, the task illuminance in the space was significantly fluctuated according to the change of outdoor daylight illuminance, especially when an unshielded photosensor was used.
5. The linear correlation between the fluctuation of outdoor vertical illuminance and photosensor illuminance was the weakest for the partially-shielded photosensor. This implies that the partially-shielded photosensor contributes to reducing the illuminance fluctuation in the space under partly cloudy sky conditions. The partially-shielded conditions reduced the fluctuation of electric light output by 67% compared to the cases of unshielded conditions when horizontal blind was used.

### 5. Limitation and future works

The factors that influence the outdoor daylight illuminance were the conditions of clouds, for example, the area, thickness and density of clouds in the sky. Under the same altitude condition, the fluctuation range of daylight illuminance might be very low or significantly great depending on the conditions of clouds. However, their influence on the fluctuation was not considered in the prediction models. Although the effect of cloud condition was not considered in the model, it appears that the data used for the prediction models indicated that the fluctuation range was significantly affected by the presence of clouds when the altitude was high.

This study was performed for limited period. The winter condition that causes the lowest solar altitude among four seasons was not considered in this study. Additional works should be performed to examine the impact of lower solar altitude on the fluctuation of outdoor daylight illuminance.

### References


