Simulation Study of Automated Blinds Control Strategy for Minimizing Cooling and Lighting Energy Consumptions

L. Xiao¹, F. Wang²,*, Y. Gao², T. Gong², Y. Di², Y. Qian², and X. Luo²

¹ School of Mechanical Engineering, Tongji University, Shanghai, 200092, China
² School of Architecture, Tsinghua University, Beijing, 100084, China

ABSTRACT
This paper proposes an optimal blind automatic control strategy, which is to set the optimal slat angle to block direct solar radiation and let maximum diffused daylight enter room for sunny day and set the optimal slat angle to let maximum daylight enter room for cloudy day. For the purpose of verifying the energy saving effect of the proposed control strategy, the outdoor and indoor solar radiation and illuminance at different blind slat angles are measured on a typical cloudy day and a sunny day. The measured data are used to calculate the cooling and lighting energy consumptions and compare with two common blind cases, which are fully opened blind (similar to no blind) case and fully closed blind case. The comparison results show that the optimal blind slat angle control can save cooling and lighting energy by about 60% comparing with the fully opened blind case, which is the largest energy consumption case. Comparing with the blind fully closed case, the optimal blind slat angle control can save cooling and lighting energy by about 50%.

KEYWORDS
Optimal Control, Automated blinds, Cooling energy consumption, Lighting energy consumption

INTRODUCTION
Daylight is an important resource in buildings. Although artificial lighting is often used in modern buildings, how to take advantages of daylight to save energy is also a hot topic. Daylighting has the advantages that cannot be replaced by artificial lighting. It can create a healthy and exciting working environment, improve occupants’ efficiency and productivity, and is beneficial to occupants’ physical and mental health. In addition, the proper use of sunlight can save energy by reducing the lighting energy consumption. Modern office buildings tend to use a lot more transparent glass, which brings visual comfort to people but challenges the HVAC designers at the same time. In summer, particularly in the cooling period, excessive solar radiance will lead to

* Corresponding author email: flwang@tsinghua.edu.cn
additional cooling energy consumption. Because the thermal resistance of windows has always been a weak point, even with vacuum glass or low-e glass, it is difficult to reduce the heat transfer coefficient of glass down to 1W/m². Besides, too much sunlight entering into the room, especially on the work area, it easily leads to glare problem, which should be avoided.

Venetian blinds are a common type of shading devices, which can be installed indoors or outdoors. Occupants can adjust the position of the lower end of a blind and the slat angle according to their needs. However, many surveys have showed that when occupants pull down the blinds, they often do not reopen the blinds, which will cause the unnecessary blockage of sunlight. Although the frequency to change blind state do not have a concrete conclusion, the unweighted average of 42 buildings investigation by Kevin (Wymelenberg 2012) reveals that just 15% of blind states were daily changed. Similar studies have also showed that 35% of blinds are not changed over a period as long as 4 months (Pigg et al. 1996). There have been many scholars studying the patterns of occupant interaction with window blinds. Because of individual differences, the requirements of occupants adjusting blinds vary from people to people. Nevertheless, the main factors which affect people’s adjustment of blinds are as follows: orientation, weather condition, the illuminance on the working area, the solar radiance level, which provides important direction for automated blinds design. Only the blinds design based on occupants’ behavioral pattern can created a satisfying working environment and make people feel comfortable.

Automated blinds can adjust blind position or slat angle automatically according to outdoor environment. On the one hand, it can block direct sunlight; on the other hand, diffuse sunlight can be introduced to meet the working illuminance requirement. Moreover, automated blinds have great potential on energy conservation in buildings. In winter, automated blinds are beneficial for allowing daylight through the windows so that the room’s temperature can be increased and people may feel more comfortable, so that the heat load can be reduced and energy can be saved. In transition seasons, as air conditioning is not available, properly adjusting automated blinds can efficiently decrease lighting energy consumption. During the cooling period in summer, if excessive solar radiation enters a building when slat angle is not at a proper position, it may cause additional cooling energy consumption, although the lighting energy consumption may be reduced. Therefore, to achieve the minimum energy consumption of cooling and lighting, the blinds must be properly controlled.

In this paper, the optimal internal blinds control strategy was study to achieve the minimum energy consumption of cooling and lighting. The solar heat gains, indoor illuminance levels, outdoor solar radiance, and outdoor illuminance levels at different time with different slat angles were measured at a south-orientated room. The measured data were used to calculate the lighting energy and cooling energy used for removing solar heat gain at different slat angle to find out the optimal slat angle. Ji-Hyun Kim has done similar experiments, but he only studied two cases of blinds fully closed and blinds fully opened (Kim et al. 2009). In this paper, the blind
slat angle was considered, which can achieve more energy savings than only control
blinds fully opened or fully closed.

CALCULATION OF THE ENERGY CONSUMPTIONS OF ARTIFICIAL
LIGHTING AND COOLING AT DIFFERENT BLIND SLAT ANGLES
To evaluate the energy saving performance of automated blinds, it is necessary to
calculate the cooling and artificial lighting energy consumptions with different blinds
control strategies. We used two typical days’ measurement data, which are clear sky
and partly cloudy sky, as samples for the energy calculation.
We studied an office room located in Beijing, with the size of width 5 m, length 5 m,
and height 3 m, with a 2×4m window facing to south, with no obstructions around the
room. Luminaires consist of six 36W twin tube fluorescents. In order to compare the
effect of automated blinds on the cooling and lighting energy consumptions in
different control strategies, six cases were designed for analysis, detailed information
is shown in table 1.

<table>
<thead>
<tr>
<th>Case</th>
<th>Blind condition</th>
<th>Weather condition</th>
<th>Cooling energy consumption (kWh)</th>
<th>Lighting energy consumption (kWh)</th>
<th>Overall energy consumption (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Blinds fully closed</td>
<td>Cloudy</td>
<td>0</td>
<td>1.296</td>
<td>1.296</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sunny</td>
<td>0</td>
<td>1.296</td>
<td>1.296</td>
</tr>
<tr>
<td>2</td>
<td>Blinds fully opened</td>
<td>Cloudy</td>
<td>1.213</td>
<td>0.216</td>
<td>1.429</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sunny</td>
<td>1.774</td>
<td>0</td>
<td>1.774</td>
</tr>
<tr>
<td>3</td>
<td>Slat angle is 60°</td>
<td>Cloudy</td>
<td>0.058</td>
<td>0.972</td>
<td>1.030</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sunny</td>
<td>0.065</td>
<td>0.648</td>
<td>0.713</td>
</tr>
<tr>
<td>4</td>
<td>Slat angle is 90°</td>
<td>Cloudy</td>
<td>0.165</td>
<td>0.648</td>
<td>0.813</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sunny</td>
<td>0.191</td>
<td>0.576</td>
<td>0.767</td>
</tr>
<tr>
<td>5</td>
<td>Slat angle is 120°</td>
<td>Cloudy</td>
<td>0.245</td>
<td>0.36</td>
<td>0.605</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sunny</td>
<td>0.216</td>
<td>0.432</td>
<td>0.648</td>
</tr>
<tr>
<td>6</td>
<td>Slat angle is 150°</td>
<td>Cloudy</td>
<td>0.885</td>
<td>0.648</td>
<td>1.533</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sunny</td>
<td>0.225</td>
<td>0.72</td>
<td>0.945</td>
</tr>
</tbody>
</table>

Four typical blind slat angles were selected in cases 3 to 6 separately, which can check
the effect of different slat angles on the cooling and lighting energy consumptions.
Additionally, the cases 1 and 2, which are the blinds were fully opened and fully
closed respectively, are used to comparing with cases 3 to 6 to check the influence of
automated blinds to the cooling and lighting energy consumptions.
The measured data on April 20\textsuperscript{th} (partly cloudy sky) and May 20\textsuperscript{th} (clear sky) are used
to calculate the energy consumptions. On April 20\textsuperscript{th}, only when slat angle was 150°
can direct solar radiation entered the room through the window, and there was no
direct solar radiation entering the room at the four slat angels on May 20th because of
high solar altitude.
Because in the cooling energy consumption only the part of removing radiation solar
heat gain relates to blind control, the radiation solar heat gain through window is used
to represent the influence of blind control on cooling energy consumption. The total
solar heat gain was calculated by multiplying the projection area of the window on the
horizontal plane, which can be calculated by solar altitude angle and window area, by
measured solar heat gain per unit horizontal area. The cooling energy is calculated by
dividing the radiation solar heat gain by the cooling system energy efficient rate
(EER), as shown in Equation 1. A typical EER value of 3.0 is used for the calculation.
The energy calculation results are shown in table 1 and the hourly solar altitude angle
and window area horizontal projection are shown in table 2.

Table 2 The solar altitude and window area on two measurement days

<table>
<thead>
<tr>
<th>Time</th>
<th>Weather condition</th>
<th>The solar altitude angle (°)</th>
<th>The window area in a horizontal plane (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>Cloudy</td>
<td>48.950</td>
<td>6.967</td>
</tr>
<tr>
<td></td>
<td>Sunny</td>
<td>55.550</td>
<td>5.488</td>
</tr>
<tr>
<td>11:00</td>
<td>Cloudy</td>
<td>57.087</td>
<td>5.178</td>
</tr>
<tr>
<td></td>
<td>Sunny</td>
<td>64.849</td>
<td>3.756</td>
</tr>
<tr>
<td>12:00</td>
<td>Cloudy</td>
<td>61.181</td>
<td>4.401</td>
</tr>
<tr>
<td></td>
<td>Sunny</td>
<td>69.880</td>
<td>2.931</td>
</tr>
<tr>
<td>13:00</td>
<td>Cloudy</td>
<td>59.498</td>
<td>4.713</td>
</tr>
<tr>
<td></td>
<td>Sunny</td>
<td>67.469</td>
<td>3.319</td>
</tr>
<tr>
<td>14:00</td>
<td>Cloudy</td>
<td>52.831</td>
<td>6.065</td>
</tr>
<tr>
<td></td>
<td>Sunny</td>
<td>59.352</td>
<td>4.740</td>
</tr>
<tr>
<td>15:00</td>
<td>Cloudy</td>
<td>43.339</td>
<td>8.478</td>
</tr>
<tr>
<td></td>
<td>Sunny</td>
<td>48.872</td>
<td>6.986</td>
</tr>
</tbody>
</table>

\[
E_i = \frac{\sum_{i=1}^{n} (Q_i S_i)}{EER}
\]  \hspace{1cm} (1)

where \(Q_i\) and \(S_i\) is hourly measured solar heat gain per unit horizontal area and the
calculated projection area of the window on the horizontal plane, respectively, and
\(EER\) is the cooling system energy efficient rate.
The lighting energy consumption was calculated by multiplying the luminaire power
density by the floor area where the illuminance level does not reach the required
illuminance threshold, which is 300lux according to design manual (Lu et al. 2008).
According to the same design manual the luminaire power density is set at \( 11 \, \text{W/m}^2 \). The lighting energy consumption calculation is shown in Equation 2.

\[
E_2 = \left\{ \sum_{i=1}^{n} \left[ 0.036 \text{Roundup}\left( \frac{11A_i}{36} \right) \right] \right\}
\]

Where \( E_2 \) is daily lighting energy consumption (kWh), \( A_i \) is the hourly floor area where the illuminance level does not reach 300 lux, 11 is the luminaire power density, and 36 is the wattage of twin tube fluorescents.

**RESULTS**

Case 1: blinds fully closed
In this case, the solar heat gain was considered to be zero, and luminaires need to be used in all areas in any period of working hours. Owing to the solar radiation can enter room only during 10:00 to 15:00 on April 20th and May 20th, we only took this time period into consideration. Consequently, both the cloudy day and the sunny day consumed 1.296 kWh of lighting energy. That is to say the overall energy consumptions of cooling for removing solar heat gain and lighting are 1.296 kWh.

Case 2: blinds fully opened
For the case of blinds fully opened (same as no blind situation), the lighting energy consumption in cloudy day and sunny day were 0 and 0.216 kWh respectively. The cooling energy consumptions in cloudy day and sunny day were 1.213kWh and 1.774kWh respectively. As a result, the overall energy consumptions in cloudy day and sunny day were 1.429kwh and 1.774kwh respectively. Compared with case 1, when blinds were fully closed in cloudy day, although the solar heat gain was zero, which caused zero cooling energy consumption, the luminaires were needed in any period of time to ensure indoor illuminance as being required. Therefore, the lighting energy consumption was the largest. While for case of blind fully opened, despite the lighting energy consumption was the least, the cooling energy consumption was the most. As a result, the overall energy consumption in case 1 was less than that in case 2. This contrast was more apparent in sunny day.

Case 3-6: slat angle were 60°, 90°, 120°, 150° respectively
The blind slat angle definition is as shown in Fig.1. When the blinds are at the horizontal position, the angle is 90 degrees. The energy consumptions under various slat angles were shown in Table1. From Table1 it can be seen that for both weather conditions of cloudy and sunny sky, cases 3-6 consumed less energy than case 1, i.e. blind fully closed case, and case2, i.e. blind fully opened case.
For the various blind slat angle cases (cases 3-6), on April 20th when direct sunlight entered the room, i.e. the slat angle was 150°, the solar heat gain became the largest. The cooling energy consumption decreased accompanying to the slat angle decrease. However, the lighting energy consumption was not the least when direct sunlight entered the room through the window. Instead, when the slat angle was 120°, because of plenty diffuse sunlight introduction, the overall energy consumptions achieved the minimum value. On May 20th, when there was almost no direct sunlight entering the room because of high solar altitude, the cooling energy consumption showed a trend that gradually increased and the lighting energy consumption firstly decreased and then increased, accompanying to the slat angle increase, as shown in Fig.2 and Fig.3. Besides, the overall energy consumptions also reach to the minimum value when slat angle was 120°, as shown in Fig. 4. The overall energy consumptions of setting slat angle at 120° were less than the blind fully opened case, which is the largest energy consumption case, by 57.7% and 63.5% on April 20th and May 20th respectively. Comparing with the blind fully closed case, the blind slat angle at 120° can save cooling and lighting energy by 53.3% and 50.0% on April 20th and May 20th respectively.

If the blind slat angle control strategies can be further refined, the overall energy consumptions can be further reduced. As an example, if a slightly more detailed slat angle control strategies are set as follows, the overall energy consumption can be reduced by 1.8% and 14.2% on April 20th and May 20th respectively comparing with the fixed slat angle of 120°.

On April 20th: slat angle is 120° from 10:00 to 13:00 and 90° from 14:00 to 15:00, the overall energy consumptions will be 0.594kWh.

On May 20th: slat angle is 90° at 10:00, 60° from 11:00 to 13:00 and 120° from 14:00 to 15:00, the overall energy consumptions will be 0.556kwh.
Figure 2. The cooling energy consumption at different slat angles

Figure 3. The lighting energy consumption at different slat angles
CONCLUSIONS
The energy consumptions of lighting and cooling for removing radiant solar heat gain under different slat angle control strategies were calculated. The results show that:
1) For both weather conditions of partly cloudy and sunny sky, the overall energy consumptions with blinds fully closed and blind fully opened were more than that of slat angles can be adjusted.
2) As a rule of thumb, for the two measurement days’ weather conditions, if the slat angle is set at 120°, the overall energy consumptions of lighting and cooling can be reduced by about 60% comparing with the blind fully opened case.
3) If a little more detailed blind slat angle control strategies are employed, for example to change the slat angle two to three times in one day, the overall energy consumptions can be further reduced by 1.8% to 14.2% comparing with the fixed slat angle at 120° for the two measurement days’ weather conditions.

REFERENCES