Potential lighting and thermal demand reduction in office buildings using blind control considering surrounding buildings

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ABSTRACT
Automated blind control has been found to be more effective in controlling solar penetration than manual blind operation. Existing automated blind control methods mainly focus on improving indoor conditions, but considering the outside obstructions may offer a potential method to admit diffused solar radiation, reducing lighting, cooling, and heating demands. Accordingly, in this study, blind control considering surrounding buildings (BCCSB) was applied to determine potential demand reductions considering 20,736 cases of different surrounding building heights, orientations, locations, and climate change projections using EnergyPlus. The results demonstrate that BCCSB can reduce lighting demand by up to 30% when the building obstruction angle is greater than 30°; however, this reduction decreased as the angle factor between the fenestration surface and sky decreased due to the accompanying reduction in admitted diffused solar radiation. The reduction in lighting demand also reduced the cooling demand as fewer active lighting fixtures were required. The use of BCCSB did not significantly reduce heating demand. The BCCSB can thus facilitate the reduction of lighting and cooling demand in highly glazed buildings, especially in warm climates. This evaluation of the positive effects of BCCSB can help to develop related design guidelines, standards, and practices for automated blind control strategies.

1. Introduction
The glass areas of office building façades have been increasing for purposes of facilitating visual comfort, psychological comfort, health, and productivity (Boyce, Hunter, and Howlett 2003). However, large-windowed areas may cause the indoor air conditions of a building to become heavily dependent on solar radiation that can increase cooling demand and visual discomfort due to the admission of radiant heat through the windows. A commonly used method to mitigate this potential negative effect is using adjustable blinds that allow solar radiation to enter according to need. Nevertheless, previous studies have revealed that the low frequency of manual blind operations can result in glare or undesirable blockage of daylight (Kim et al. 2007; Rea 1984).

To provide more effective blind usage, automated blind control has been studied by many researchers to increase the positive effects and decrease the negative effects of admitted solar radiation (Meerbeek et al. 2014; Thalfeldt and Kunimitsu 2015; Yeon et al. 2019; Karlsen et al. 2016). Increased penetration of direct and diffused solar radiation through windows can decrease heating and lighting demand. As a result of this decreased lighting demand, cooling demand may also be reduced. However, increased admission of solar radiation through a window will also increase cooling demand and the possibility of glare.

In office buildings, avoiding visual discomfort should be a priority for maintaining a productive working environment for occupants. In addition, previous studies have stated that occupants typically manually adjust blinds to prevent glare rather than heat (Raja et al. 2001; Foster and Oreszczyn 2001). In order to avoid glare, the possible direct solar radiation penetration of the fenestration surface could be calculated beforehand to block solar access using the blind. The key factors that need to be considered for solar penetration calculations are the solar path and solar profile angle on the window surface; these can be predicted using the specific location and orientation of the building and its possible obstructions. Most previous studies have used the specific location and orientation of the subject buildings to determine novel blind control strategies; however, previous studies have rarely considered obstructions, such as surrounding buildings (Koo, Yeo, and Kim 2010; Seong, Yeo, and Kim 2014, CEN EN 15193, 2007; Reinhart 2002; Chan and Tzempelikos 2013). As blind control has a wide range of possible impacts on lighting, cooling, and heating demands, possible changes in demand due to surrounding buildings should be considered for automated blind control.

Conventional methods for preventing visual discomfort often do not consider surrounding buildings, and instead focus on blocking solar penetration with the...
help of solar profile angle calculations. However, when direct solar radiation is blocked by surrounding buildings, blinds can be opened to let in diffused solar radiation, reducing heating and lighting demand while maintaining visual comfort. The efficacy of blind control when taking account the surrounding obstructions varies according to building location (i.e., latitude and longitude, which determine the solar profile angle) and climate conditions. In this study, the positive effect of blind control considering surrounding buildings (BCCSB) on lighting, cooling, and heating demand reduction was evaluated via quantitative analysis. Due to the significant variations in surrounding building orientations and climate conditions, possible influencing factors were classified into building aspect and climate condition aspects. In the building aspect, building orientation, which can significantly change the solar profile angle, and surrounding building heights, which can block direct solar radiation, were considered. In the climate condition aspect, various climate types in different locations and climate change scenarios for each chosen climate were assessed because different climate types not only include varying solar profile angles on the fenestration surface depending on the solar path but also influence the relative significance of blind control according to different lighting, cooling, and heating demands.

2. Concept of BCCSB and simulation setup

2.1. Conventional blind control and methods for considering surrounding buildings

The primary focus of conventional automated blind control in an office building is to provide visual comfort by preventing direct solar radiation at the reference point. The reference point is where the occupant's desk is expected to be, as shown in Figure 1. The typical reference point is 1.5 m away from the window and at a height of 0.762 m (Shen, Hu, and Patel 2014). In order to block direct solar radiation beforehand, the solar profile angle on the fenestration surfaces should be calculated using the solar altitude angle and solar azimuth as described in Figure 2 and according to the following equation:

$$\tan(\Omega) = \frac{\tan(\beta)}{\tan(\gamma)}$$

where $\Omega$ is the solar profile angle, $\beta$ is the solar altitude angle, and $\gamma$ is the solar azimuth. The solar altitude and azimuth change depend on the date, local standard meridian, longitude, latitude, and surface orientation angle. Among the factors used to calculate the solar profile angle, the location of the building would change the position of blinds the most. For example, blind control methods to prevent solar penetration in Incheon and Sydney will have significant differences due to their differences in solar profile angles. Most of the solar radiation would penetrate the fenestration surface facing south in Seoul, while in Sydney solar radiation would penetrate the north-facing surface. Due to the distinctive differences in blind control to prevent solar penetration in different climates, various locations should be evaluated to determine the characteristics of possible blind control strategies.

In conventional blind control, the blind height for preventing solar penetration is determined by calculating the possible direct solar radiation at the reference point without considering the surrounding buildings. This study aims to observe the impact of automated blind control considering the surrounding buildings, and therefore the predetermined solar profile and azimuth angles governing blind operation take the surrounding buildings into account by opening the blind when the surrounding buildings block the solar radiation, as illustrated in Figure 3. A detailed description of the concept of BCCSB has been provided in (Seong 2015). In Figure 4, the sun path is indicated in yellow and the time zone for blind control opening occurs when the sun is not blocked by the surrounding buildings. The blind position that determines the height of the blind is indicated by a green line and is set to open such that the...
surrounding buildings block any direct solar radiation. In a hot climate, the benefits of this novel strategy would be promising; however, it must be noted that the cooling demand may be increased on account of increased diffused solar radiation permitted into the building.

### 2.2. Simulation setup

#### 2.2.1. Building boundary conditions

The BCCSB was evaluated using various adjustments in terms of building and climate aspects through simulations. The building simulator software EnergyPlus v.8.8 was used to obtain the heating, cooling, and lighting demands in numerous cases. To determine the effects of BCCSB application in a typical small office building, the geometry and internal load conditions of a reference building from the U.S. Department of Energy (DOE) were used (Deru et al. 2011). The reference building used was in a temperate climate zone, such as Chicago. The boundary conditions of the building are described in Table 1. The reference building consists of a thin layer of insulation and a double-glazed bronze tinted and clear glass window. To determine the effects of BCCSB on the building heating and cooling demands, thermal comfort was maintained using a module built in the IdealLoadSystem of EnergyPlus to maintain the exact heating and cooling setpoint temperatures of the target zone. Lighting demand was calculated by assuming the use of dimming control, which would maintain the brightness at the reference point at 400 lux.

To determine the influencing factors of the building aspect, different target building window orientations and surrounding building conditions were considered. The possible orientations of the target building window were set as north, south, east, and west, and the surrounding buildings were placed on the left, centre, and right side facing the window, as shown in Figure 5. The equivalent floor area of the target building was used in the surrounding buildings and their heights were adjusted considering the obstruction angle as defined by the Building Research Establishment (BRE) (Littlefair 1991). The obstruction angle is the degree from the center of the window to the top of the surrounding building; an increment of 15° was used to evaluate different potential surrounding building heights, as illustrated in Figure 6.

#### 2.2.2. Climate conditions

Influencing factors in terms of climate conditions were adjusted by considering different locations on the basis of climate classification and climate change scenarios. The Koppen and Geiger climate classification is one of the most widely used and updated
classifications (Kottek et al. 2006; Peel, Finlayson, and McMahon 2007). Among 31 climate classifications, the five main classifications are based on vegetation and expressed in capital letters as follows: equatorial (A), arid (B), warm temperate (C), boreal (D), and polar (E). The selected evaluation locations considering climate classification, latitude, and longitude were Ceará (A), Riyadh (B), Sydney (C), Helsinki (D), and Reykjavik (E), as indicated in Figure 7. In addition, Incheon (C) was used to observe the results of a difference in location rather than in climate classification. The IWEC weather files for the six evaluated locations were used as the current weather conditions.

In order to evaluate the efficiency of BCCSB under future climate conditions, dynamic simulations using future weather files were applied in this study. The Climate Change World Weather File Generator (CCWorldWeatherGen), created by Jentsch was used to produce these future weather files (2008). The CCWorldWeatherGen uses a morphing methodology (Belcher, Hacker, and Powell 2005) to incorporate climate change predictions made by a coupled atmosphere-ocean general circulation model, the Hadley Centre Coupled Model version 3 (HadCM3), into the current weather files (in epw format), which are available for more than 2100 locations around the world (“EnergyPlus EnergyPlus Weather Data” 2016; Jentsch, Bahaj, and James 2008). The resulting changes in temperatures and cloud cover are shown in Figure 8.

Table 2 lists the parameters used to create the models. Four orientations, six obstruction angles of three surrounding buildings, six locations, two climate scenarios, and two blind control strategies (conventional and BCCSB) were considered resulting in a total of $4 \times 6^3 \times 6 \times 2 \times 2 = 20736$ scenarios run to evaluate the possible demand reduction resulting from the application of the BCCSB.

### Table 1. Simulation conditions.

| Condition                              | Definition                                                                 |
|----------------------------------------|---------------------------------------------------------------------------|
| Blind                                  | External venetian blind with high reflectivity slats (80%) with fixed blind angle |
| Window to wall ratio                   | 0.44                                                                      |
| Floor area                             | 511 m² (27 m × 18 m)                                                     |
| Ceiling height                         | 3.05 m                                                                   |
| Maximum internal heat gain             | People 18.58 m²/person, lighting 19.48 W/m², and equipment 10.76 W/m²   |
| Infiltration rate                      | 0.4 ACH                                                                  |
| U-values                               | Wall: 0.7 W/m² K, Windows: 3.2 W/m² K                                    |
| Solar heat gain coefficient            | 0.39 (double-glazed window)                                              |
| Room setpoint temperature              | 20°C (heating), 26°C (cooling)                                           |
| Target lux                             | 400 lux at the reference point                                           |
| Climate conditions                     | Current weather: International Weather for Energy Calculations (IWEC)    |
|                                       | Climate change: medium emission scenario for the 2080s (2079–2099)       |

### Figure 5. Model overview showing surrounding building adjustments.

### Figure 6. Adjusting surrounding building heights according to obstruction angle.

### 3. Results and discussion

#### 3.1. Potential lighting, cooling, and heating demand reduction depending on surrounding buildings

The conventional blind control strategy to prevent only solar penetration was compared with the BCCSB. The surrounding building heights were increased equally to identify the magnitude of the potential lighting, cooling, and heating demand reductions due to BCCSB according to the location and orientation of the building window with the...
results expressed in Figure 9. When the building window faced west, lighting demand could be decreased in all locations as the blind was open when the surrounding buildings blocked the direct solar radiation. When the height of the surrounding buildings was 4.55 m with an obstruction angle of 30°, lighting demand was reduced the most because the blinds were opened more, allowing more diffused solar radiation through the window into the building. However, the positive effect of accepting diffused solar radiation decreased when the surrounding building heights were increased to 11.25 m and higher, decreasing the diffused solar radiation as the angle factor between the window surface and the sky decreased. The latitude of the city had a significant influence on the other orientations. Ceara and Riyadh did not benefit from blind control because their latitudes were so close to the equator that solar profile angles were very large and thus rarely changed the blind control state. Because Sydney is below the equator, lighting demand was decreased when the building window faced north, while because Helsinki, Reykjavik, and Incheon are located further above the equator, lighting demand was reduced when the building window faced south.

When more diffused solar radiation is allowed into a building, cooling demand can increase, representing a negative effect of reducing the lighting demand. However, when the lighting demand decreased, cooling demand also decreased because the magnitude of
the decreased cooling demand as a result of turning off lighting devices was significantly larger than the increased cooling demand due to more incoming diffused solar radiation. The percentage of cooling demand reduction varied depending on the cooling demand in each evaluated city. When the total cooling demand was large, there was a relatively smaller reduction in cooling demand. For example, cooling demand in Reykjavik decreased close to 100% because there is barely any cooling demand in a polar climate. For the same reasons, the heating demand reduction was not appreciable because the expected demand reduction from the increased transmission of diffused solar radiation was significantly less than the heat produced after turning on more lighting devices.

In order to evaluate the impact of surrounding building positions, three buildings of equivalent size were placed on left, center, and right side of the window equipped with BCCSB, as illustrated in Figure 5. The height of each surrounding building was adjusted and the resulting maximum possible lighting, cooling, and heating demand reductions are shown in Figure 10. A similar phenomenon occurred in terms of lighting, cooling, and heating demand when the surrounding buildings were changed by equal increments of height. Blind control considering the center surrounding building indicated the most savings of each of the three

### Table 2. Simulation cases.

| Building orientation | Surrounding building location | Surrounding building height (obstruction angle) | Climate aspect | Blind control strategy |
|----------------------|------------------------------|-----------------------------------------------|---------------|------------------------|
| North                | Left                         | No building (0°)                              | Incheon       | Conventional blocking of direct solar radiation only |
| South                | Center                       | 2.95 m (15°)                                  | Ceara         | Blocking direct solar radiation considering surrounding buildings |
| East                 | Right                        | 4.55 m (30°)                                  | Helsinki      | Block direct solar radiation considering surrounding buildings |
| West                 |                              | 6.65 m (45°)                                  | Reykjavik     | Block direct solar radiation considering surrounding buildings |
|                      |                              | 11.25 m (60°)                                 | Riyadh        | Block direct solar radiation considering surrounding buildings |
|                      |                              | 21.25 m (75°)                                 | Sydney        | Block direct solar radiation considering surrounding buildings |

**Figure 9.** Potential demand reductions when applying BCCSB in various locations.

**Figure 10.** Maximum possible lighting, cooling, and heating demand reductions.
surrounding building locations and was almost equivalent to the cases in which all three surrounding buildings were considered, as shown in Figure 9. Thus, in the initial stage, the proposed blind control should at least consider the presence of an adjacent building located in front of the subject window.

Because the percentage of maximum possible demand reduction occurred when the building window faced west and the height of the surrounding building was 30°, the absolute lighting, cooling, and heating demand reduction in kWh per floor area was compared for this configuration with the results shown in Table 3. Although the percentage of cooling demand reduction in Reykjavik is significant in Figures 8 and 9, the magnitude of cooling demand reduction is negligible. Notably, the reduction in lighting demand was a dominant factor in decreasing the cooling demand using the proposed blind control method.

### 3.2. Impact of climate change

Future weather files were used to evaluate the potential reduction in lighting and thermal demand resulting from the application of the proposed blind control when accounting for climate change. The application of climate change increased the overall outdoor dry-bulb air temperature and the accompanying maximum possible lighting and cooling demand reductions are shown in Figures 11 and 12, respectively. Again, only lighting and cooling demand were plotted because no significant effect on heating demand was observed. In Figure 12, most locations demonstrated improvements in lighting and cooling demand when using blind control in the future because of the increase in overall solar radiation due to the increased transmission of diffused solar radiation through the opened blind. However, the percentage of cooling demand reduction decreased under future weather conditions because the total cooling demand

![Figure 10. Potential demand reduction according to height change of a single surrounding building.](image)

| Location | Ceara | Riyadh | Sydney | Helsinki | Reykjavik | Incheon |
|----------|-------|--------|--------|----------|-----------|---------|
| Lighting reduction [kWh/m²] | 5.41 | 5.42 | 7.73 | 6.74 | 10.78 | 9.27 |
| Cooling reduction [kWh/m²] | 0.58 | 0.62 | 0.29 | 0.24 | 0.01 | 1.04 |
| Heating reduction [kWh/m²] | - | - | - | - | - | - |

![Table 3. Maximum demand reduction for a west-facing building window at each evaluated location.](image)
increased, proportionally decreasing the overall effectiveness of blind control.

4. Conclusions

The effects of the BCCSB were evaluated by investigating the possible lighting, cooling, and heating demand reductions. To consider various uncertainties including building and climate condition aspects, various cases considering the orientation, surrounding building heights (i.e., obstruction angles), locations, and climate change conditions were simulated to determine the efficacy of the proposed blind control.

(1) As surrounding building heights increased, approximately 20–30% lighting demand reduction was achieved under an obstruction angle of 30°. However, lighting demand reduction decreased as the angle factor between the fenestration surface and the sky was reduced, particularly once the angle of visibility became greater than 45°.

(2) The lighting demand decreased due to the penetration of increased diffused solar radiation, and because fewer lighting fixtures were turned on to maintain the target brightness, the cooling demand decreased while the heating demand barely changed.

(3) The greatest lighting demand reduction was observed in buildings with windows facing west. For south or north facing building windows, location played an important role as the possible solar profile angle significantly changed depending on the latitude.

(4) When adjusting the surrounding building heights, it was observed that an adjacent building in the front centre of the subject window had the greatest influence on demand reductions. Therefore, in the early stages of the design phase, it is advisable to apply BCCSB when a nearby building is located in front of the target window.

(5) Future projections of climate change indicate that the need for lighting may increase; however, the reduction of cooling demand would be smaller when using BCCSB as changing climate conditions will lead to an increase in the overall cooling demand.

Determining the possible reductions of lighting, cooling, and heating demands when using BCCSB could help define the magnitude of potential savings and initiate the development and application of methods to account for the details of surrounding buildings in standards, research, and practice. In future studies, a simplified BCCSB method and tools to evaluate the possible demand reduction when accounting for surrounding buildings can be developed for practitioners. Moreover, sensitivity analysis of different building uses, types, and window configurations should be investigated.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Engineering and Physical Sciences Research Council [EP/R008612/1].

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