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Comparative control strategies for roller shades with respect to daylighting and energy performance

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ABSTRACT

Traditionally, automated shading operation includes open-closed strategies trying to maintain a comfortable environment while controlling glare and solar gains. Four different dynamic shading control strategies with constant and variable set points were developed and studied in this paper using year-round transient integrated thermal and lighting simulation, to investigate their impact on outdoor view, daylighting metrics, thermal loads and energy consumption as well as on excessive illuminance that can cause visual discomfort in private offices. The strategies and generic and can be applied to any location, orientation and climate if appropriate set points are selected.

The results showed that: (i) shades remain open for a significant portion of working hours depending on orientation and weather conditions (ii) controlling shades based on solar radiation as suggested in previous studies might not be an effective method; instead, illuminance thresholds are probably more appropriate (iii) the third control strategy leads to reduced source energy consumption and maximized daylight utilization; however, careful consideration of interior illuminances is needed to avoid the risk of glare; (iv) differences in annual source energy consumption between control strategies range from 10.1% to 34.4% depending on glazing and shading properties and (v) different strategies should be used in different orientations. Validation of results with full-scale experiments is presented for representative cases. The interactions and integration between daylighting benefits and thermal requirements need to be studied through the interplay between lighting energy use, solar and internal heat gains, while considering comfort parameters that vary depending on the shading control strategy used.
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1. Introduction

Interior roller shades are widely used in office spaces to control solar heat gain and prevent visual discomfort. Their properties have significant impact on space daylight availability, and hence on energy demand for space lighting, heating and cooling. Recent studies on automated operation of shading devices have shown great a potential for energy savings [9,13,18,20]. Various shading control algorithms have been used in existing literature: for example, based on transmitted or incident beam solar radiation [7,17,18]; based on incident total irradiation or internal temperatures [6,9,12]; and others with diverse performance [15,23]. Currently, advanced whole building simulation programs including EnergyPlus [4] have already integrated deterministic shading control patterns based on a variety of parameters such as work plane illuminance, glare indices, solar radiation, temperature and thermal demands, although the shading positions are limited to fully on and fully off conditions [2].

Generally, in existing literature, the same parameter threshold (or set point) is applied to all space design alternatives (e.g. space dimensions, window size, space orientation, shading properties). For example [21], assumed that the shading device is lowered completely when direct sunlight is present; Ref. [7]suggested that the shades should close when the transmitted direct solar radiation is higher than 94.5 W/m^2; and in Ref. [5] shades were actuated if vertical solar irradiation was higher than 300 W/m^2, without differentiating between different space dimensions, window size or shading properties. More recently, researchers have studied the different criteria used in shading control intending to achieve a generalized approach [22]. investigated the impact of set point (the vertical irradiation on external façade) on space daylight autonomy and energy demand. They claimed that the different activation levels (100, 150 and 200 W/m^2) in the cut-off angle control of venetian blinds do not significantly affect the energy demand although the daylight autonomy increased for Frankfurt and Rome. However, Wankanapon and Mistrick's study (2011) reported

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significant difference in total energy consumption for a cooling dominated region which is attributed to the different set points of incident solar radiation on façade (95, 189 and 400 W/m^2). Moreover, controlling shades automatically based on glare indices may not be always easy or realistic. With available detailed characterization of glazing and shading systems careful decisions on control parameters, set points and thresholds are required. Considering glare control, it may as well be more reasonable to use illuminance rather than solar radiation as a criterion for automated shade operation as explained in this paper. Ref. [19] reviewed the various criteria for adjustment of shading position and reported that shading control methods can influence the ranking of transparent façade alternatives. In all previous studies, roller shades can be only set to two positions: completely closed or open. This may reduce provision of useful daylight, or cause visual discomfort and/or overheating.

This paper investigates the impact of existing and new shading control strategies on office space energy performance and daylighting metrics using year-round transient thermal and lighting integrated simulation [18]. For office spaces, the most important function of interior roller shades is to block direct sunlight so that the occupants are not disturbed by glare. Therefore four different shading control strategies are developed and modeled to maximize daylight utilization, minimize energy consumption and reduce the risk of visual discomfort according to different shading properties. Space lighting, heating and cooling demand, total source energy consumption and daylighting metrics are compared for every strategy to analyze their efficiency and draw useful conclusions.

2. Description of shading control strategies and summary results for a perimeter office

The description of the four types of shading control algorithms is presented in detail in the following sections, using a private office space as an example. The office has one exterior façade with one window facing south (window size: 3 m × 1.6 m high, window-to-wall ratio WWR = 40%). Window framing accounts for 10% of the total window area (U-value = 6.42 W/m^2 K). The transparent part of window is a double-clear glazing (visible transmittance: 0.786, solar transmittance: 0.607 at normal incidence, U-value: 2.689 W/m^2·K). The interior roller shades have a transmittance of 10%, a front side reflectance of 60% and a back side reflectance of 30%, which are common values for existing products. The space dimensions are 4 m × 4 m × 3 m high. The interior surface reflectances of the floor, ceiling and walls are 45%, 80% and 50% respectively. The exterior surface absorptance of the external façade is 60%. Occupant density in the space is 0.11 p/m^2 (working hours: 9:00 am–5:00 pm) and sensible heat gain from each occupant is 76 W. The equipment load factor of the space is 5.4 W/m^2 during office hours [1]. The lighting system is continuously dimmable to compensate daylighting illuminance so as to reach the requirement of 500 lux on the work plane (0.8 m above floor). The lighting system has a power density of 10 W/m^2 (T-5 lamps) with 30% of the released heat convected directly to the air [1]. The other 70% of the heat released by lights goes to all surfaces as internal radiative heat gains according to their respective area-absorptance weights. Heating and cooling are always available throughout the year. The heating set point during office hours is 22 °C and 18 °C otherwise. The cooling set point during office hours is 24 °C and 26.6 °C otherwise. The heating system consumes natural gas (80% efficiency) and the cooling system consumes electricity (average COP of 3.5). These values are typical and were used to convert thermal loads to source energy use (source-site ratios are 3.34 for electricity and 1.047 for natural gas).

Philadelphia was used as the location for this introductory example. Weather data information for Philadelphia were obtained from TMY3 weather data [14] and the Perez et al. model [16] was used for prediction of diffuse solar radiation and incident direct and diffuse illuminance on each facade. Hourly data is interpolated into 15 time steps in the simulation.

Daylighting and energy performance are listed in Table 1. Evaluated performance metrics include daylight autonomy (DA), useful daylight illuminances (UDI), fraction of time when work plane illuminance exceeds the recommended value or is lower than the recommended value, annual lighting, heating and cooling energy demand and site energy consumption per unit floor area and total annual source energy consumption per unit floor area. The results are based on the finite difference thermal network approach and a radiosity-based method with one-bounce ray-tracing described in Ref. [18] —a validation section with experimental measurements is also presented later in this paper. For office spaces, the work plane illuminance requirement is 500 lux and is usually preferred to be below 2000 lux to avoid visual discomfort [3,11]. So 500 lux and 2000 lux are used as “critical” values for the daylighting performance evaluation. Three bins within that range (100–500 lx, 500–1000 lx and 1000–2000 lx) are used to calculate separate UDI values.

Note that the shading control methods and set-points are described in detail in the following sections. In the results of Table 1, the following shading control set points were used: SC-I: 20 W/m^2 incident; SC-II: 9000 lx transmitted; SC-III: 9000 lux-45000 lux transmitted; SC-IV: SC-III mode plus cooling mode (solar gains control).

2.1. No shading control

Completely open and closed shade conditions were first studied as two extreme shading control methods that provide reference results. Apparently, closed shades result in low daylight autonomy and increased lighting energy use. Although open shades allow significant amounts of natural light into the space, they are not a realistic scenario since glare problems are inevitable—work plane illuminance exceeds 2000 lx for 86.5% of the time and the maximum daylight autonomy is 17.3%. For the space and mixed climate considered, cooling requirements are higher when a single south-facing window is present. The total annual source energy consumption (air-conditioning and lighting) is equal to134.1 kWh/m^2·year with closed shades, 15% higher than open shades (116.9 kWh/m^2·year).

In the following sections, the automated shading control strategies are developed with a view to allow longer periods of outside view, shorter periods of extreme (high or low) illuminances, higher DA and UDI and lower energy demand and consumption.

2.2. Shading control strategy I (SC-I)

The first shading control has been used in existing literature. The interior roller shades close completely if incident solar radiation exceeds a certain value (Fig. 1 (a)). Various criteria were used in previous studies [19,22,24]. In this section, three different criteria are first compared: shades automatically close completely when:

(i) Incident beam radiation on the façade is present (in this case we use a small threshold of 20 W/m^2) during office hours (9 am–5 pm);
(ii) Incident beam radiation on façade exceeds 100 W/m^2;
(iii) Incident total solar radiation on façade exceeds 200 W/m^2;
(iv) Incident total solar radiation on façade exceeds 400 W/m^2 during office hours.

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