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Solar shading control strategy for office buildings in cold climate

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ABSTRACT

The objective of the present study was to develop a solar shading control strategy for venetian blinds applied on office buildings in cold climates in order to achieve acceptable energy use and indoor environmental performance. A control strategy based on a combination of internal and external shading develop within the Norwegian R&D project "Fasader i glass som holder hva vi lover" ("*Glazed facades keeping what we promise*", translation by author) was extended with factors related to glare, daylight sufficiency and view to the outside. The study used full-scale experiments in a test room in Aalborg, Denmark, to verify the performance of the control strategy, and the study was further expanded with annual simulations of the office room at different locations. Results of the annual performance illustrated that the proposed control strategy would lead to satisfying compromises between the energy and indoor environmental performance. Generally, the investigation exemplifies the importance of doing integrated evaluations of energy use and thermal and visual comfort when making decisions regarding solar shading control strategies.

1. Introduction

Modern office buildings often consist of a high proportion of glazing in the façade, which requires considerable attention during the building design with respect to its impact on occupant comfort as well as on energy demand for cooling, heating and lighting. Use of solar shading to control solar radiation through the glazed openings is usually essential in office buildings in order to obtain visual comfort, thermal comfort as well as a decreased energy use for cooling.

Solar shading systems can be static or dynamic. Results from an investigation by Nielsen et al. [1] indicate that dynamic solar shading solutions function better than static solutions in the Danish climate. This is true both with respect to energy demand and reduction of overheating, as well as it allows for daylight supply and view to the outside when there is no need for solar shading. Winther [2] and Liu [3] also confirm the improved building performance by applying dynamic solar shading on different buildings in Denmark; they claim that use of intelligent dynamic facades are essential in achieving the high building performance required in the future.

1.1. Control of dynamic solar shading

From an energy point of view, automatic control should be applied on dynamic solar shading in office buildings, since research shows that users of the building do not tend to manually change the solar shading position for the short-term events in the outdoor weather conditions and the blind rate of change for manually systems is commonly rather low [4–6].

Results from one of our earlier studies indicate the importance of considering user-accepted solar shading control strategies during building design in order to be able to make realistic building performance predictions [7]. A number of researchers state the significance of making integrated evaluations of daylight, thermal comfort and energy use when selecting a solar shading system and control strategies since an appropriate solution might be a compromise between these aspects [1,8–12].

Research shows that people in indoor spaces generally like access to a window for daylight provision and outside view (e.g. [7,13–15]). Bakker et al. [16] emphasise that the balance between preventing glare and providing daylight to the room as well as a view to the outside are important issues in any solar shading control strategy. Venetian blinds are a flexible solar shading solution with adjustable slat angles where the view to the outside can be maintained at many slat positions, as well as the fact that the slats can change the direction of the incident light which makes it a good

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solution for daylight control [17]. This may be the reason why Kirimtat et al. [18] found that venetian blinds are the most commonly studied shading device during the last decades.

Several simulation studies have used venetian blinds with a cut-off strategy of the slats to achieve a balance between preventing glare and providing daylight supply as well as a view to the outside [19–22]. However, the cut-off strategy might be insufficient to avoid glare [7,21,22]. In order to provide sufficient glare-free daylight, Chan and Tzempelikos [21] suggest controlling the solar shading according to Daylight Glare Probability (DGP), either continuously controlled using real-time DGP simulation or pre-calculated correlations between transmitted illuminance and DGP. Yun et al. [23] also consider DGP as a control criterion for obtaining visual comfort within an office building. However, they conclude that this metric is impractical for calculating in real scenes and, therefore, suggest implementing vertical eye illuminance (E_v) as a control criterion. E_v is the vertical illuminance at eye level of a seated person, approximately 1.2 m above floor level. Other researchers, e.g. [24,25], have also suggested control of vertical illuminance for achieving visual comfort.

Solar irradiance is a simple and relatively common parameter used in solar shading control [4,5,12,26–28]. Van Den Wymelenberg [5] finds evidence in reviewed literature of a solar irradiance based blind control predictor used as a proxy for occupants' interactions with window blinds. However, the literature suggests that there is a wide disparity among the irradiance values to use, ranging from approximately 100–450 W/m^2, and a variety of locations to detect the irradiance [5]. When trying to find the correlation between solar radiation and the occupants' interactions with solar shading, it would be preferable to assess the transmitted solar radiation which is the condition experienced by occupants. However, O'Brien et al. [4] found that a significant part of the studies in the literature only considers external conditions, probably since it is easier to measure.

Van Moeseke et al. [12] study the impact of control rules on the efficiency of shading devices for a two-person office room located in Belgium. They found that strategies based on both the external irradiance and the internal temperatures were more efficient to balance comfort and energy savings compared to strategies based on solar irradiation or internal temperature alone. Use of the combined criteria ensures better utilization of solar gains for heating during winter and may limit the time of closed mode and, thereby, increase the visual contact with the exterior as well as inlet of daylight.

Use of solar shading during night time might have an insulating effect and, according to Grynning et al. [29], it may contribute to a slight reduction in the annual net energy demand in cold climates. According to Bryn [30], the potential improvement of the *U*-value of the window system when applying solar shading depends on the initial *U*-value of the window, the insulation and emissivity of the solar shading and the air tightness of the cavity between the window and the solar shading. Oleskowicz-Popiel and Sobczak [31] investigated the effect of roller blinds on heat losses through a double-glazing window during the heating season in Poland. With roller blinds tightly closed during the night hours, an insulated external roller blind and an internal textile roller blind contributed to about 45% and 33% energy saving respectively for an uncoated glazing and 44% and 29% respectively for a low-E coated glazing.

The Norwegian R&D project "*Glazed facades keeping what we promise*" (FG project) evaluates different functions of solar shadings both with respect to daylight, thermal comfort and reduction in energy use to cooling and heating. The FG project developed a control algorithm which utilises a combination of internal and external solar shading, as proposed in Ref. [32], with the aim of improving thermal comfort as well as reducing the energy use, see Ref. [33]. The objective of the present study is to continue with the work conducted within the FG project by extending the control algorithm with factors relating to glare, daylight sufficiency and view based on findings in the literature in order to obtain a realistic control strategy that balances the aspects of thermal and visual indoor environmental performance and energy demand. Use of full-scale measurements in an experimental room located in Aalborg, Denmark, will verify the performance of the control strategy.

2. Control algorithm

The control strategy is divided into two main parts: work hours and outside work hours. During the work hours, the main goal is to obtain occupant comfort. In this mode the control strategy focuses on avoiding glare and overheating while also, when possible, ensuring satisfactory daylight supply and view to the outside by utilizing the estimated cut-off angle of the slats in activated state, i.e. the angle where direct solar radiation is prevented while providing maximum view contact to the exterior. However, the minimum tilt angle of the slats is set to 15° in order to avoid negative cut-off angles in situations with large solar altitude angles and, thereby, avoiding view to the sky and high risk of glare [34]. An initial version of the proposed control strategy for work hours was applied in an earlier reported occupant survey, see Ref. [7]. Results from this survey indicated that view is an important factor for occupant comfort in a work environment and that the participants appreciated the view gained through tilted solar shading blind slats in activated position compared to closed slats in activated position. It was further found that the initial version of the control strategy was associated with relatively high occurrence of glare. Improvements made for the present proposal of the solar shading control strategy is that the tilt angle is step-wised increased in case the cut-off angle is insufficient in avoiding glare. Additionally, the set-point of vertical eye illuminance, which is used as an indication of glare, is lowered from 2000 lx to 1700 lx based on findings reported in Ref. [35]. Use of vertical eye illuminance as activation criteria and application of tilted blind slats in activated position are the main new features compared to the strategy presented in the FG-project.

The cut-off angle is calculated according to Eq. (1) [36] where *d* is the profile angle of the sun, *s* is the spacing between the slats, *w* is the width of the slats, α is the solar altitude angle and γ is the solar surface azimuth. When activated, the blind shades the whole window and all the slats have the same tilt angle.

$$\beta_{\text{cut-off}} = \sin^{-1}\left(\cos(d) \times \frac{s}{w}\right) - d \tag{1}$$

$$d = \tan^{-1}\left(\frac{\tan\alpha}{\cos(\gamma)}\right) \tag{2}$$

Outside work hours, energy saving is the main focus, and the solar shading is utilized both as an insulating layer to reduce heat loss during cold periods as well as a protecting shield against excessive unwanted solar gains during cooling-dominated periods (Fig. 1).

3. Verification of solar shading control performance

3.1. Test facility

In order to verify the performance of the control strategy, it is implemented in a full-scale test facility located at Aalborg University, Denmark (latitude 57.02°N, longitude 10.0°E), see Fig. 2. The test facility, named the Cube, has previously been used by Kalyanova [37] to investigate double-skin façades, by Winther [2] and Liu [3] to explore intelligent glazed facades and by Le Dréau [38] to investigate radiant and air-based heating and cooling systems. The set-up from Le Dréau has been kept and extended for the present survey. The following sections will give a short description of the test facility, for further details see Ref. [38] Part II.