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Determining the energy performance of manually controlled solar shades: A stochastic model based co-simulation analysis

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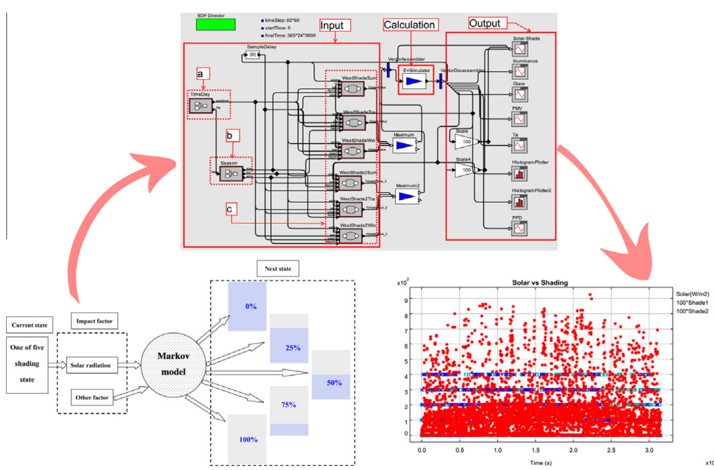
HIGHLIGHTS

- Driving factor for adjustment of manually controlled solar shades was determined.
- A stochastic model for manual solar shades was constructed using Markov method.
- Co-simulation with Energyplus was carried out in BCVTB.
- External shading even manually controlled should be used prior to LOW-E windows.
- Previous studies on manual solar shades may overestimate energy savings.

GRAPHICAL ABSTRACT



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ABSTRACT

Solar shading devices play a significant role in reducing building energy consumption and maintaining a comfortable indoor condition. In this paper, a typical office building with internal roller shades in hot summer and cold winter zone was selected to determine the driving factor of control behavior of manual solar shades. Solar radiation was determined as the major factor in driving solar shading adjustment based on field measurements and logit analysis and then a stochastic model for manually adjusted solar shades was constructed by using Markov method. This model was used in BCVTB for further co-simulation with Energyplus to determine the impact of the control behavior of solar shades on energy performance. The results show that manually adjusted solar shades, whatever located inside or outside, have a relatively high energy saving performance than clear-pane windows while only external shades perform better than regularly used LOW-E windows. Simulation also indicates that using an ideal assumption of solar shade adjustment as most studies do in building simulation may lead to an overestimation of energy saving by about 16–30%. There is a need to improve occupants' actions on shades to more effectively respond to outdoor conditions in order to lower energy consumption, and this improvement can be easily achieved by using simple strategies as a guide to control manual solar shades.

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1. Introduction

The building sector consumes 40% of the world's energy [1] and thus there is a great need to save building energy consumption by using effective measures [2–4]. Solar shading devices can be used to control solar heat gain and regulate the admission of daylight, thus it has a significant impact on cooling, heating and lighting energy consumption of a building [5,6]. To reduce energy use in buildings while maintaining a comfortable indoor thermal and visual environment, it is crucial to apply appropriate building energy efficiency measures such as shading devices [7–9]. Compared to fixed shading, adjustable solar shades are more welcome because they can block excessive solar heat gain in summer and admit sunlight to warm indoor space by controlling shade angle or position.

1.1. Models for manual shade control

Currently, manually controlled solar shades, due to their relatively low costs compared to automatically ones, are widely used in buildings in hot summer and cold winter region of China for building energy efficiency. When trying to adopt solar shades in the design stage, most designers and researchers may ideally consider that occupants will always keep solar shades at an effective position in controlling the admission of solar radiation and daylight when influencing factors (such as solar radiation [10,11], glare indexes [12–14] and illuminance [15,16]) rise above a certain threshold. Furthermore, occupants' behavior of adjusting shading devices in most building simulation programs (DOE-2 [17], Energyplus [18], TRNSYS [19], Esp-r [20], DeST [21,22] etc.) is still treated as deterministic with a defined schedule of season [18] or a certain threshold as above factors. This not only crudely oversimplifies reality, but also neglects the variability caused by the diversity in human behavior, since occupants are not all that positive in controlling solar shades in reality. Thus it leads to an inaccurate simulation result (overestimation or underestimation) of the impact of manually controlled shading devices on building performance due to the stochastic character of user behavior [23].

Actually, solar radiation, occupants' visual and thermal preferences, personal values, economics and even emotional conditions etc all have a significant influence on the adjustment behavior of solar shades as illustrated in Fig. 1. Therefore, it is theoretically essential to understand how all these factors influence actions on shades if we want to determine solar shading states. And this leads to the filed study on the relationship between potential influence factors and shade use. For example, Inoue et al. reported that blinds were not closed when direct solar radiation was less than 11–58 W/m^2 and they also found that blind occlusion increased significantly with the incident depth of sun penetration [24]. Sukru's study [25] showed that about 75% of blind closures occurred when horizontal irradiance values were higher than 200 W/m^2. Based on a measurement on eight southeast facing offices in France, Sutter et al. reported the mean vertical illuminance for blind closure was 41,000 lux and 13,000 lux for blind opening [26], while it was 50,000 lux and 25,000 lux, respectively, for 10 offices in Germany according to Reinhart's study [27]. Other researchers such as Inkarojrit [28], Littlefair [29] and Foster [30] all conducted similar studies and a comparison of these findings can be found in two critical review papers [31,32].

Though solar radiation, temperature, illuminance etc can be determined by observation, occupants' visual and thermal preferences, personal values, economics and even emotional conditions etc (see factors in dashed box in Fig. 1) are hard to be determined quantitatively. Moreover, personal emotional condition difference also exists [33] even observable factors keep in same conditions. Rubi et al. [34], Lindsay and Littlefair [35], Rea [36] and Newsham [10] have reported that the control behavior of solar shades between different occupants differs significantly.

Therefore, predicting human behavior of solar adjusting seems to be an impossible task due to the stochastic character of user behavior [23]. Fortunately, modeling occupants' behavior using a probabilistic approach allows for a more reasonable account of our observation-based knowledge. Such a probabilistic approach can be considered either as a consequence of an inside uncertainty for unreachable but existing impact factors. Thus, it is very important to give an insight into the user behavior on manually adjusted solar shades.

By now, there are only a few studies on modeling stochastic behavior of manually controlled solar shades. Nicol et al. used binary logit model to carry out a probabilistic analysis for stochastic behavior on blind control (fully closed or fully open) in UK, Europe and Pakistan. Their study showed that blinds adjusting behavior link to mean outdoor temperature since there is an increase in the proportion of blinds lowered as outdoor temperature rises [37].

Haldi and Robinson also used logit regression to infer a probability distribution between blind closing and the whole range of temperatures (both indoor and outdoor) [38]. They suggested that thermal stimuli play an important role for the prediction of actions on blinds and outdoor temperature could be retained as a major driving stimulus.

They further [39] analyzed the occupancy, thermal and visual parameters that influence adjusting behavior on shading devices based on a 5-year observation on 14 south-facing cellular offices in Switzerland. Their study indicated that visual stimuli are strongly associated with actions on blinds. They also proposed an approach for a comprehensive stochastic model for simulating blind usage with the proportional odds model giving a probability for the unshaded fraction. Similar models, based on logit regression, can also be found in Inkarojrit's research [28].

These studies provide useful references for analyzing stochastic behavior of shade control. However, the models proposed by these papers cannot be used in hot summer and cold winter zone which locates at the south center of China. The weather conditions (outdoor temperature, solar radiation etc) in this area are different from those in the above studies. Moreover, differences of occupants' thermal and visual comfort preference etc may also exist between different countries. Therefore, stochastic behavior of manually controlled solar shades in this area may also have its own character.

More importantly, there still remain some restrictions in their stochastic models. For example, Nicol et al. only considered two shading states (fully open and fully closed) which are not in accord with the real condition of partly closed shades. Although Haldi and Robinson improved the model by predicting shaded fraction through a Weibull distribution function, this function may be restricted to limited cases. Therefore, a better stochastic behavior model is needed which should consider more shading states and predict shade adjustment behavior based on real statistical data without having to use an assumed function.

1.2. Simulation methods for manual shade control

To quantify the energy saving potential of manual shading devices, building simulation technologies were widely used by researchers. In building simulation, manual shading devices were normally considered to operate under automated shading control strategies among which solar radiation was the main parameter used to trigger the shade position. For example, Tzempelikos and Athienitis [40] assumed that the roller shading device is automatically closed when beam solar radiation incident on the window is higher than 20 W/m^2 for glare protection while Lee and Selkowitz