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Model-based shading and lighting controls considering visual comfort and energy use

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Abstract

Dynamic facades with high performance glazing and shading systems have the potential to balance daylighting needs, comfort and energy use, when integrated with lighting and thermal system controls. This paper presents the development and implementation of model-based control (MBC) algorithms for shading and lighting operation, aiming at minimizing lighting energy use while satisfying glare constraints. A fast and reliable lighting-glare model was used to compute real-time interior lighting conditions, lighting energy use and daylight glare probability, for predetermined shade positions (10% increments) at each control time step, based on the readings of two sensors on each building facade. Three visual comfort criteria (DGP, vertical and work plane illuminance) were embedded and compared in the real-time shading control logic, which selects the highest shade position (maximum daylight utilization) that satisfies the visual comfort criteria at each time step. The approach is similar to an optimization scheme for discrete shade positions, using visual comfort constraints as a priority, but here it is applied efficiently with a semi-analytical model in real-time control.

The developed MBC strategies were successfully demonstrated in office spaces, controlling shades and electric lighting in real-time, using simple sensor readings as inputs. An innovative, variable control interval logic was also developed and implemented, resulting in reduced shading operation without sacrificing the benefits, creating less disturbance for occupants and extending equipment life. Finally, the developed MBC strategies were evaluated using annual simulation, in terms of frequency of shade movements, annual percentage of working hours with risk of glare, lighting energy use, and fraction of outside view.

Keywords: Model-based control; Shading; Lighting; Visual comfort; Energy

1. Introduction

Energy efficiency and human comfort in buildings are the top priorities in building design and operation. Commercial buildings in the United States consumed $5.27 \cdot 10^{12}$ kW h of energy in 2013 (EIA, 2015). More than one third of the electricity consumed in commercial buildings is due to electric lighting. Therefore, reducing lighting energy use is a major goal toward overall energy efficiency in buildings.

Properly designed and controlled fenestration systems, coordinated with lighting operation, should provide natural light while ensuring occupant comfort under changing weather conditions, reducing electric lighting demand and energy use. To evaluate the impact of advanced control strategies, accurate and efficient models of dynamic façade and lighting systems are needed, as well as proper comfort indices, for use in smart automatic control algorithms (Lindelof, 2009) and overall strategies. Model-based control (MBC) strategies that use (detailed or low-order)

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models with real-time input data and robust control schemes have a great potential to reduce energy use and improve indoor environmental comfort. Most of the studies in this field have focused on thermal/HVAC system operation (Li et al., 2015; Moroşan et al., 2010; Privara et al., 2011; Derakhtenjani et al., 2015; Cai and Braun, 2015, Pengfei et al., 2015) and indoor air quality control applications (Lu et al., 2011), with embedded optimization techniques (Li et al., 2015; Hu and Karava, 2014).

However, only a few studies applied MBC strategies for lighting and shading controls (Le et al., 2014; Gruber et al., 2014), initiated by Mahdavi (2008). Thorough work on blind controllers with multi-objective optimization processes and extensions to user wishes (Daum and Morel, 2010; Guillemin and Molteni, 2002) provide advanced and promising solutions. Fisher et al. (2012) utilized an accurate model trained by measured data from light sensors located at every seat for multi-preference electric lighting control. Kim and Park (2012) used EnergyPlus as a model-based predictor to obtain optimal slat angles within a 24 h time horizon-with high computational effort. Shen et al. (2014) studied independent open and closed loop strategies for shading and lighting, as well as integrated controls including temperature and occupancy information. Recently, Bueno et al. (2015) developed a new Radiance-based modeling approach (Fener) for analysis and control of complex fenestration systems, which couples daylighting and thermal modeling in a time-step basis. This model, which uses BSDF data and the three-phase method, can be used to implement advanced shading control algorithms.

Very few studies directly associated visual comfort or glare indices with shading controls (Oh et al., 2012), although daylight glare is one of the primary reasons for interacting with shading systems. Wienold (2007) used the simplified Daylight Glare Probability approximation (DGPs) to evaluate the efficiency of shading controls toward glare –however, the strategies were not based on glare but only evaluated in terms of it. Similarly, Yun et al. (2014) used DGP to evaluate blind control strategies toward glare and energy and first stated that E_v is a good criterion for shading control. However, from their correlations with DGP and DGPs, it is implied that no direct light conditions were met. Obtaining real-time DGP data is challenging. As the DGPs approximation uses only vertical illuminance, which can be measured or simulated in real time, the potential of a model-based control based on DGPs is promising (Konstantzos et al., 2015).

Recent MBC studies on shading and lighting require real-time detailed simulation and extensive sensor networks for acquiring necessary information with changing weather and sky conditions. In addition, improper or separate controls for façade and lighting systems could be ineffective and costly. Therefore a low-cost but reliable integrated shading and lighting model-based control, with less exogenous inputs is desired. In that way, model-based control algorithms could be effective in management of façade, interior lighting and comfort (Mahdavi, 2008). Moreover, previous studies focused on venetian blinds; application to roller shades is quite limited, although simple and advanced heuristic control rules have been developed (Tzempelikos and Shen, 2013).

This paper presents the development and implementation of shading and lighting model-based control algorithms, based on visual comfort criteria, for perimeter zones with interior roller shades. The control strategies were implemented in full-scale offices and were able to minimize lighting energy use while maintaining visual comfort. Advanced control options that consider variable control intervals were developed and implemented. Finally, applications in annual building simulation are discussed.

2. Integrated shading and lighting model-based control

The flowchart of the developed integrated model-based control (MBC) is shown in Fig. 1. The logic consists of the following steps. Details on implementation and device controls are presented in a later section.

2.1. Model inputs and sensor readings

Beam and diffuse (sky and ground-reflected) transmitted illuminance through the window (calculated or measured by sensors for real-time control, or TMY3 data for an

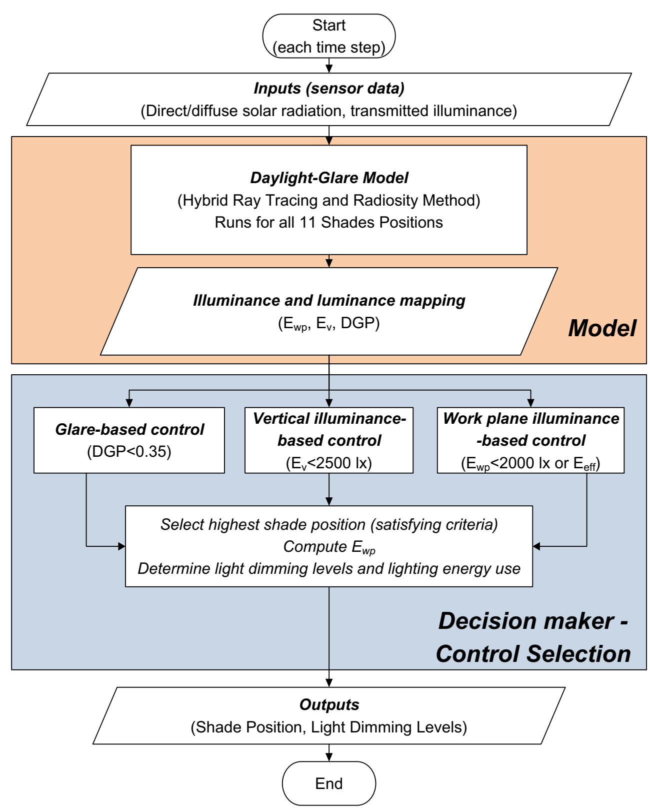

Fig. 1. Flowchart of the developed model-based shading and lighting control.