Automation in Construction 92 (2018) 133–150

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Assessing the energy and daylighting impacts of human behavior with window shades, a life-cycle comparison of manual and automated blinds

Amir Nezamdoost*, Kevin Van Den Wymelenberg, Alen Mahic

University of Oregon, Energy Studies in Buildings Laboratory, Eugene & Portland, OR, USA

ARTICLE INFO

Keywords:
Manual blind use
Automated blind operation
LM-83
Lightswitch
Blindswitch
Spatial daylight autonomy
Annual sunlight exposure
Life-cycle analysis

ABSTRACT

Manual and automated blind controls are typically not included in energy and daylight simulation in part because there is no consensus in the research or practice communities about the way users operate manual blinds or override automated blinds. In order for blind use patterns to become part of energy and daylight simulation best practices, the range of annual energy and daylighting impacts associated with blind use must be understood. This paper addresses these aspects by comparing four leading candidates of manually-controlled blinds plus two automated blind control algorithms using a high-rise office building located in Boise, ID. This study revealed that all four current "manual" blind use algorithm choices perform relatively similarly to automated systems, and surprisingly sometimes even more efficiently. LM-83 currently has the lowest average occlusion during regularly occupied hours, followed by Lightswitch-2002, while Blindswith-A and -B have the highest average occlusion. The IES-recommended manual blind algorithm resulted even in lower average blind occlusion and lighting energy consumption than automated systems. Finally, life-cycle cost analysis was calculated. The results show that the cost savings from interior automated shading system are substantial over a 30-year time horizon, when compared with common passive manual blinds ($25 versus $7.6 Net Present Value per SF glazing area).

1. Introduction

Daylighting is a common energy-efficiency strategy that also boasts a myriad of other human benefits [17,26,27,30,39]. Successful daylighting design that saves energy and improves human satisfaction incorporates many technologies, spans several disciplines, and requires attention to detail throughout the design process and implementation.

Blinds are quite common in spaces designed for daylighting (12 out of 22 spaces in one field study per [8,24,25]), since most daylighting designs will include some period of low angle sunlight, causing intermittent glare and require mitigation. The impact of manual and automated blinds on the performance of daylighting and energy consumption in buildings has been a subject of some inquiry [1,2,4,19–21,31,38]. According to Laouadi [14], when closed, blinds reduce solar heat gain by 40% with high-performance windows to 50% with conventional windows in comparison to unshaded windows. Due to daylight penetration impact, blinds can significantly alter interior lighting loads in systems with daylight sensing electric lighting controls [6,38].

There is a growing need to evaluate the impact of automated blind controls as an energy efficiency measure, and the baseline assumptions of the presence and/or operation of manual blinds are critical to such an evaluation. A few studies have examined the benefit of internal automated blinds in lab or field settings [4,12,15,35] and reported savings in peak cooling load (5–30%), cooling and ventilation energy savings (10–30%), lighting energy savings (20–45% compared to systems with photocell dimming and static blinds) and total energy savings (25%) for all systems. However, the assumptions about the baseline presence and operation of manual blinds vary in these studies.

There are a limited number of studies that have provided behavioral models for manual operation of interior blinds. One of the leading manual blind control algorithms, Lightswitch-2002, was developed by Reinhart [31]. According to this algorithm, blinds are assumed to be fully occluded when the transmitted vertical irradiance exceeds 50 W/m2 and fully raised at the start of the following workday. Another algorithm was proposed by Lee and Selkowitz [16] to predict the operation of interior venetian blinds on an hourly basis in response to incident radiation values that are either above or below 95 W/m2 threshold. Inkarojrit [10] developed a probabilistic model which predicts the probability that a shading device will be lowered based on the intensity of transmitted vertical irradiance. In 2010, the IES Daylight Metrics Committee proposed a manual blind control algorithm and published it as part of IES LM-83 [7–9], which adjusts blinds based upon maintaining a threshold of less than 2% of a simulated interior

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* Corresponding author.

E-mail address: amirn@uoregon.edu (A. Nezamdoost).

https://doi.org/10.1016/j.autcon.2018.03.033
Received 5 July 2017; Received in revised form 14 November 2017; Accepted 29 March 2018

horizontal sensor grid exceeding 1000 lx of direct beam sunlight with zero light bounces via digital simulation. Van Den Wymelenberg [38] proposed two manual blind control algorithms as a product of a literature review, and these were coined “Blindswitch-2012A” and “Blindswitch-2012B” by Dyke et al. [4]. Blindswitch-A adjusts the blind occlusion (increased window occlusion as more blinds close) according to the sunlight penetration depth and whether exterior direct normal irradiance exceeds 120 W/m^2. Blindswitch-B regulates occlusion based upon vertical exterior illuminance. The Blindswith-2012 models differ from previous models in that they only apply the algorithm to a portion (60%) of the window blinds and set other blinds (40%) to various fixed positions.

In order to compare the manual algorithms noted above, a study was designed using to a large open plan office on the 2nd floor of a high rise building located in Boise, ID, USA; in order to evaluate the performance and possibly refine previous proposed window shade behavioral models. We selected four candidates and compared them with two automated interior blind control algorithms.

The automatic systems were also analyzed in this paper including one interior automated shade, Automated Algorithm A, and it adjusts the shades based on vertical interior illuminance behind the window (darkness and brightness thresholds of 500 and 6000 lx respectively) and the sunlight penetration depth in the space. The other automatic system is Automated Algorithm B for automated interior/exterior blinds. According to this algorithm, the blind occlusion changes based upon exterior vertical illuminance of a façade measured at the rooftop weather station and calculated direct sun penetration depth into the space.

Further details for each algorithm are provided in the methods section. This paper compares the annual energy and daylighting performance impacts of each blind algorithm relative to one another and to multiple baselines. One baseline assumes blinds are always open and another assumes blinds always closed (best- and worst-case scenarios). All scenarios assume functional daylight sensing lighting controls. The paper also examines the frequency of blind movements - Rate of Change (ROC) and Number of Blind Movement (NBM) - and average window occlusion results, spatial daylight autonomy (sDA), annual sunlight exposures (ASE) and Life Cycle Cost Analysis (LCCA), for each blind algorithm relative to data from existing literature in order to support dialogue and eventual adoption of a consensus-based manual blind use algorithm and set of best practices for blind algorithms (both manual and automated) in daylighting and energy simulations.

2. Methods

2.1. Case study

This paper examines a large open plan office on the second floor of a high-rise building located in downtown Boise, ID. USA (Figs. 1 and 2). The case study building has an area of approximately 24,546 m^2 (264,218 ft^2), has modest core zones and abundant open and private offices around the perimeter. The second floor (38,218 ft^2 area) has 112 double pane windows. The windows have a head height 3.6 m (11.7 ft) and the sill is at 0.25 m, thus the windows are 3.35 m (10.8 ft) tall. Windows wrap all facades and make up a window-to-wall ratio of 54.81% for the 2nd floor. Window U-value of 1.82 W/m^2-K (0.32 Btu/h-ft^2-F), solar heat gain coefficient (SHGC) of 0.42 and visual light transmittance (VLT) of 0.72 are used throughout. Exterior walls and roof U-values are 0.25 and 0.11 W/m^2-K (0.043 & 0.019 Btu/h-ft^2-F), respectively. The built-up HVAC system for the second floor comprises: water-to-air heat pumps at each zone, a 90% efficient boiler to provide heat to the water loop, and a chiller (COP = 5.5) to absorb the heat from the water loop. The equipment power density is 8.29 W/m^2 (0.77 W/ft^2) and total installed lighting power density (LPD) is 11.46 W/m^2 (1.07 W/ft^2). It was estimated that 125 occupants were on the second floor, during regular working hours (from 8 am to 6 pm, Monday through Friday). The building rotation is 35° clockwise from the North axis. Simulations were conducted with typical meteorological year 3 (TMY3) dataset for Boise, ID. This building and climate were selected for the case study because of the large floorplate, multiple orientations, skin dominated building, and relatively extreme climate.

Fig. 1. Case study building.

2.2. Blind control algorithms

Six blind control algorithms (four interior manual blind use algorithms and two interior/exterior automated blind control algorithms) were applied blinds, which were used as the primary shading devices, in order to compare their relative differences (Fig. 3) in operation patterns and resultant annual energy and daylighting impact.

2.2.1. Introduction of control algorithms

2.2.1.1. Blindswitch-A. Blindswitch-A utilizes a sunlight threshold of 120 W/m^2 of exterior irradiance measured normal to the sun and increases occlusion based on increased sunlight penetration depth [38]. As soon as sensors exceed the sunlight threshold, blind occlusion increases proportionally with sunlight penetration depth. Based upon literature review [38], the algorithm assumes that in reality there are always some blinds that remain “always engaged” and “always retracted”. Blind retraction is based upon a time delay (time-based hysteresis), serving to provide a hysteresis effect [4].

2.2.1.2. Blindswitch-B. Blindswitch-B utilizes a proportional relationship between vertical exterior illuminance and blind closure [38]. Blind closure begins when 33,000 lx of vertical exterior illuminance strikes the façade and maximum occlusion occurs at 100,000 lx. Similar to Blindswitch-A, some blinds remain retracted and some remain engaged at all times. A hysteresis effect is implemented for blind opening whereby blinds do not retract until a substantially lower exterior vertical illuminance is measured [4].

2.2.1.3. IES LM-83 metrics. The third manual blind use algorithm in this study, is based upon the simulation protocol documented in IES LM-83 [9]. The trigger value for opening or closing interior blinds (by window group) is the percentage of floor area (2%) that exceeds a simulated 1000 lx of sunlight, assuming zero light bounces and appropriate fixed architectural shading, cloud cover, and shading from trees and adjacent buildings. Furthermore, it is an interior horizontal illuminance measurement that includes hourly cloud cover, glazing VLT, and the effect of angle of incidence. In LM-83, the direct sunlight calculated for determining blind closure does not consider reflected light (zero light bounces) from exterior objects or the diffuse sky component on an hourly basis. According to LM-83 documentation, blinds are closed until less than 2% of the sensors on a 0.61 m × 0.61 m