Building and Environment 78 (2014) 155–170

Contents lists available at ScienceDirect

Building and Environment

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

Energy and visual comfort analysis of lighting and daylight control strategies

Eric Shen, Jia Hu*, Maulin Patel

Lighting Solutions and Services, Philips Research North America, 345 Scarborough Road, Briarcliff Manor, NY 10510, USA

A R T I C L E I N F O

Article history:
Received 11 March 2014
Received in revised form
16 April 2014
Accepted 27 April 2014
Available online 9 May 2014

Keywords:
Lighting
Daylight
Energy
Integrated control
Independent control
Simulation

A B S T R A C T

Shading systems have the potential to reduce energy consumption of electric lighting and improve visual comfort. Various automated control systems of shading device and electric lighting have been widely used. However, existing lighting and shading systems typically operate independently, i.e., information is not shared, and thus system performance is not optimal. Therefore, integrated control systems have been proposed to maximize energy efficiency and user comfort. Some problems are still unaddressed. For example, the benefits of sharing control information (e.g., HVAC state and occupancy information) between the lighting and shading control systems have not been quantified; the benefits of integrated controls have not been quantified. To address these issues, improved independent and integrated control strategies were proposed by adding shared HVAC state and occupancy information. To provide a quantitative comparison of these control strategies, a co-simulation platform consisting of BCVTB, EnergyPlus and Matlab was developed to perform an in-depth quantitative study of seven control strategies (manual, independent and integrated control strategies). Simulation results for a reference office building were presented for three climate zones (Baltimore, London, Abu-Dhabi), two types of blinds (interior, exterior) and two window-to-wall ratios (66%, 100%). A dynamic occupancy model was developed from actual office occupancy data and used in the simulations. The lighting, heating and cooling energy consumption, electric demand and visual comfort of different control strategies were evaluated and compared. Overall, in most cases, integrated lighting and daylight control outperforms all other strategies in energy and visual comfort performance.

1. Introduction

According to the Buildings Energy Data Book, lighting consumed about 20.2% of the commercial building energy in U.S. in 2010 [1]. It is therefore imperative to develop strategies that minimize the lighting energy usage intensity to realize low-energy sustainable buildings. Advanced lighting controls offer one of the most cost-effective means to reduce the energy, carbon footprint, and operating costs of existing buildings, and to improve occupant satisfaction by providing personal control over light conditions. Electric lighting control and daylight (blinds or shades) control are both essential for regulating interior lighting conditions. One of the methods is to exploit the daylight coming into indoor areas more effectively. If the lighting can be automatically turned off according to the level of daylight flowing indoors, the amount of electrical energy consumed for artificial lighting can be thereby reduced.

It is critical for both lighting and shading systems to complement each other to create a comfortable and productive visual environment with maximum energy efficiency. The use of on/off or dimmable lighting systems integrated with automated blinds can block direct sunlight, provide the design workplane illuminance, and save energy [2,3]. These systems can result in lighting energy savings of 30–77% [3,4]. Various blind and lighting control methods have been developed. The control strategies can be broadly divided into open-loop and closed-loop controls [5]. Open-loop blind controls are those that adjust the output based on external input only and are deployed most widely today [6–8]. Most commercially available automated venetian blinds only control the slat angles to cutoff direct sunlight [9–12]. Closed-loop strategies employ feedback along with external input to regulate the output. Integrated control of daylight and lighting involves control of electric lighting and blinds. Control of electric lighting can be simply on/off control or dimming control, and blinds can be controlled by open-loop or

* Corresponding author. Tel.: +1 914 945 6252; fax: +1 914 945 6580.
E-mail addresses: jia.hu@philips.com, hujia07@gmail.com (J. Hu).

http://dx.doi.org/10.1016/j.buildenv.2014.04.028
0360-1323/

closed-loop controls. Some advanced controls add more control variables, for example, user preferences may be integrated into the controller by automatically learning user preferences [13]. Another example of advanced control uses an adaptable hierarchical fuzzy blind controller optimized by genetic algorithms that consider various state variables [14].

Simulation tools have been widely used to evaluate the daylight and energy performance of control strategies. Based on EnergyPlus simulations, an artificial neural network based open-loop control and a simplified closed-loop control were developed to control innovative blinds that can provide better daylight and energy performance than conventional blinds [11,15,16]. A blind control was optimized to adapt to room dynamics through EnergyPlus and Matlab [17]. Shen and Hong [18] developed an integrated daylight and lighting control, evaluated the energy savings in an office model using EnergyPlus simulations, and found lighting energy savings of 64–84%, and heating, mechanical ventilation and air-conditioning (HVAC) savings from 3% to 43% depending on location, compared to a base case with clear windows and all lighting fully on. Hu and Olbina [19] developed daylight and energy prediction methods based on EnergyPlus and Radiance simulations, and found that the method can provide a fast evaluation of blind and lighting control strategies for space with combinations of different blind reflectance and glazing transmittance. Tzempelikos and Shen [20] compared four different dynamic roller shading control strategies with constant and variable set points by using a finite difference thermal network approach and a radiosity-based method [21], and found that different control strategies should be used in different orientations. Using hybrid ray-tracing and radiosity methods for calculating radiation transport and illuminance distribution [22], Chan and Tzempelikos [23] evaluated four control strategies: cut-off angle control, daylight-redirecting control, and two glare protection control modes, and found that the first two methods may cause glare, and the two glare protection control algorithms can minimize the risk of glare while still providing good daylight performance.

Even though many researches have been conducted to study the impact of control strategies on daylighting and energy performance, many problems are still left unaddressed. Many previous simulation studies were based on oversimplified settings and control strategies due to limitations on available tools and techniques. For example, the timeout period of lighting control was usually ignored; the blind control time step for closed-loop systems is usually set much longer than actual system; and many other factors (e.g., HVAC state) affecting the results are ignored and the number of control strategies evaluated is very limited. In addition, in real-world applications, lighting and blind/shade control systems typically operate independently to regulate interior illuminance while external daylight conditions vary [5,6,24]. The independent approach was found to be sub-optimal in energy efficiency and sometimes causes inconvenience to users [5,9]. These types of systems use the independent control approach where there is no sharing of information between different control systems. Occupancy sensing is an important and most ubiquitously deployed automatic lighting control strategy. Thus, this could cause impractical estimation of energy savings. The third problem with the current integrated daylight and lighting control was that the control strategies mainly focused on the integration of window and lighting control. A better control strategy could be achieved by integrating HVAC state.

Some efforts have already been done to solve some of the problems. For example, some integrated approaches, that is, integration of electric lighting control and blind control systems, have been proposed [5,18,25]. However, some of these systems are not fully integrated with HVAC systems even though the daylighting and lighting levels may significantly affect cooling and heating loads. Moreover, the benefits of the integrated control approaches have not been quantified in the literature leaving rooms for subjective interpretations.

Therefore, the aim of this research is to quantify different independent and integrated control strategies and compare energy and daylighting performance. The objectives of this research are: (1) improving the current integrated control strategies by sharing HVAC and occupancy information between different control components; (2) comparing energy and daylighting performance for independent and integrated control strategies using different cases. The comparison metrics include annual energy consumption (lighting, HVAC), electric demand and visual comfort performance (e.g., illuminance, glare).

2. Development of lighting and daylight control strategies

Seven control strategies (i.e., four independent, two integrated, and one manual control systems) are presented (see Table 1). The window blinds can be controlled either by open-loop and closed-loop control strategies. The electric lights are controlled by closed-loop.

2.1. Manual control of electric lighting and no blinds

In this control strategy, no blinds are installed and lights are manually controlled. This control strategy serves as the base case for comparing the maximum lighting energy savings with other control strategies. Lights are turned on manually when the occupant first arrives and turned off when the occupant leaves. Lighting may be kept within a minimal dimming level in some zone areas. Different dimming strategies may be used in daytime and nighttime.

2.2. Independent control strategies

Mukherjee and Birru [5] introduced prototypes of independent control of closed-loop lighting system and open-loop blind system, and independent control of closed-loop lighting system and closed-loop blind system. In this research, the occupancy sharing and HVAC link were added into the system to further improve the control performance.

2.2.1. Independent open-loop blind and closed-loop dimming control

Mukherjee and Birru [5] presented the independent open-loop blind and closed-loop dimming control strategy (see Fig. 1). In this control strategy, the electric lighting is controlled by occupancy

Table 1
Independent and integrated control strategies.

Control type	Control strategy
Manual control	Strategy 1: Manual control of lights and no blinds
Independent control	Strategy 2: Independent open-loop blind, closed-loop dimming control
	Strategy 3: Independent open-loop blind, closed-loop dimming control, occupancy and HVAC mode shared with blind system
	Strategy 4: Independent closed-loop blind, closed-loop dimming control
	Strategy 5: Independent closed-loop blind, closed-loop dimming, occupancy and HVAC mode shared with blind system
Integrated control	Strategy 6: Fully integrated lighting and daylighting control with blind tilt angle control without blind height control
	Strategy 7: Fully integrated lighting and daylight control with blind tilt angle and height control