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Toward the accuracy of prediction for energy savings potential and system performance using the daylight responsive dimming system

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ABSTRACT

This study attempts to verify the accuracy of energy savings prediction using a daylight responsive dimming system. To accomplish this, the real-time power consumption of electrical lighting in a mock-up space was compared with the power consumption that was calculated using 'the prediction method' (Method A), which was suggested to improve the accuracy of the predicted amount of energy savings. In addition, this study suggested the 'indirect illuminance' concept (Method B) to improve the system performance and predict the lighting energy savings potential of a system because certain inherent problems that are caused by the open-loop proportional control algorithm used were identified. Regarding the accuracy of the prediction method, 'Method A' considers the non-linear dimming curve of the luminaires and thus generated data that were more similar to the real measured lighting power consumptions. 'Method B' generated higher energy savings potential (e.g., 36.9–73.8%) compared with those of Method A (e.g., 27.6–72.9%) on each day.

1. Introduction

In 2014, the U.S. Energy Information Administration (EIA) reported that approximately 412 billion kWh of electricity was used for lighting by the residential and commercial sectors in the United States [1]. This amount was approximately 15% of the total electricity that was consumed by these sectors. Thus, studies of energy-efficient lighting systems, including new light sources, luminaires, lighting control, and integration with daylighting, have been conducted in an effort to reduce the energy consumed by lighting systems in the residential and commercial buildings. In particular, because there has been increasing interest in the use of daylighting, which has positive psychological and physiological effects on human beings, studies have been conducted to prevent excessive glare, reduce indoor cooling loads, and maximise lighting energy savings through the appropriate and efficient use of daylight [2–4].

A daylight responsive dimming system has the potential to maximise the energy efficiency of lighting use in buildings by controlling the intensity of electrical lighting to maintain target illuminance levels on a workplane using the detected interior luminous flux from a photosensor regardless of the amount of incoming daylight. In the past, fluorescent lamps were used primarily as indoor lighting systems but produced difficulties in the application of such a system due to the necessity of a special dimming ballast to dim the light. Conversely, LED lighting is considered to be a state-of-the-art light source that makes it easy to dim the light and thereby extend the application of such a system [5]. In addition, it is important that a daylight responsive dimming system integrate with a shading system to maximise the energy efficiency and user comfort; thus, many studies have been conducted on integrated daylighting control systems [6]. A shading system has the potential to reduce cooling loads and improve visual comfort by avoiding excessive direct sunlight; it can also maximise the available daylight by opening the shade when there is no direct incident sunlight on the building facades [7].

Thus, there has recently been increasing interest in daylight responsive dimming systems using LED lights that are integrated with a shading system to increase energy savings potential. To make such a system feasible, it is important to persuade potential clients with engineering data, including annual electrical energy savings prediction. In a daylight responsive dimming system, the amount of energy savings can vary based on many variables, such as the control algorithm used, the light sources used, the photosensors' locations and directions, and the building configuration. Therefore, it is important to accurately predict the amount of energy savings in a particular situation. Previous efforts to predict energy savings were easily performed with a simple prediction method using simulated incoming daylight levels. Based on these simulated daylight data, 'the simple prediction method' calculated the amount of elec-

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trical light required to achieve the target illuminance levels and assumed that the system was perfectly operated and maintained at the target illuminance levels. However, the real situation is not this simple or accurate.

This study attempts to verify the accuracy of energy savings prediction when using a daylight responsive dimming system. The occupant visual satisfaction is also an important factor when using this system [8], but this study focused on the lighting energy savings prediction. To accomplish this, 'the other prediction method' was suggested to generate a more accurate prediction of energy savings. In addition, this study extends the scope of this field to include the accuracy of the system performance while considering the control algorithm and calibration method used because certain inherent problems caused by the open-loop proportional control algorithm used were identified. A new concept was then suggested to easily achieve the appropriate system performance and maximise the energy savings potential. With such a concept, a more accurate system performance and a greater amount of energy savings were finally shown.

2. Previous studies

Among the studies that are related to the energy savings potential of the daylight responsive dimming system, Li et al. systematically measured and analysed the electrical lighting load, indoor illuminance, and daylight availability using the high-frequency dimming control system in an open-plan office [9]. As a result, the average illuminance level using high-frequency dimming control was approximately 480 lx, which is near the recommended illuminance of 500 lx for office spaces. The annual energy saving was 365 kWh, which was a 33% reduction in the electrical lighting energy use. Those authors concluded that the lighting energy could be reduced by more than 30% using high-frequency dimming control.

A study by Roisin et al. also compared the lighting energy savings potential in offices using different control systems for three locations in Europe [10]. The best configuration was found in a southward-orientated office in Athens. In this case, the energy savings potential was 61% of the annual energy consumption. Those authors concluded that a dimming control system is appropriate for a large space based on the visual comfort of its workers. In addition, the IDDS (Individual Daylight Dimming System) was shown to perform better when the occupancy rate was greater than 44%.

Also, two studies by Li [11] and Chow [12] analysed the lighting energy savings potential in certain place such as daylight corridor and atrium space because this places are suitable to deliver excellent lighting energy savings with the daylight responsive dimming system. Monthly lighting energy savings for the daylight corridor ranged from 179 to 259 kWh and annual saving was 2600 kWh.

To calculate the energy savings potential in a mock-up space, Mukherjee et al. conducted a study using integrated systems of daylight and electric lights [13]. Simulated and experimental results from the mock-up space were presented for the control methods: open-loop and closed-loop, independent controls of window blinds; closed-loop, independent control of electric lighting; and closed-loop, integrated control of blinds and lighting. The lighting energy savings potential was highest with the closed-loop integrated control. Lee et al. extensively considered that the installation of the daylight responsive dimming system would be easy for new buildings, but the installation of the photosensors and the associated system in existing buildings would be difficult [14].

On the other hand, Loutzenhiser et al. analysed the accuracy of a given simulation tool by comparing the measured and simulated light levels in a real building [15]. Daylighting models were constructed using EnergyPlus and DOE-2.1E software. The average differences calculated using the EnergyPlus software for the measured values of daylight illuminance and light power were within 119.2% and 16.9%, respectively; using the DOE-2.1E software, the average differences were within 114.1% and 26.3%. Many other studies of daylight responsive dimming systems have reported that the systems can result in lighting energy savings from 30% to 77% [16,17].

Due to the increasing interest in a method that accurately predicts lighting energy savings, studies of prediction methods for this value have been conducted. Li and Lam collected solar radiation and outdoor illuminance data for three years [18] and presented a simple method to predict and analyse the lighting energy savings, cooling and heating loads, and the thermal load of lighting systems. In addition, Krarti and Ihm proposed a simple method to demonstrate the validity of the method that calculated the lighting energy savings based on the visible transmittance, the window-to-perimeter floor area ratio, and the perimeter-to-total floor area ratio [19,20]. Kim et al. also calculated the lighting energy savings based on the daylight illuminance that was measured on the workplane [21]. Those authors used the relationship between the power consumption (input) and illuminance (output) based on the minimum and maximum levels using a linear equation to predict the lighting power consumption. Especially, Caicedo and Pandharipande proposed a control method for achieving minimum power consumption with maintaining a target illuminance level on a workplane using illuminance measured by ceiling light sensors [22]. The achieved lighting power savings and illuminance were found to be close to the values when the light sensors are located on the workplane.

Regarding shading systems, Koo et al. proposed a new automatic blind control method to maximise the advantages of available daylight in buildings [23]. By installing many blinds in a large space and individually controlling each blind, indoor daylight could be maximised, and occupants could be protected from glare. Li et al. also explained that existing shading devices, such as blinds, are inappropriate to be used as methods to reduce the amount of lighting energy consumed by daylight responsive dimming systems or to prevent glare from excessive direct sunlight in an open-plan office for curtain-wall buildings due to their large size [24]. Those authors installed solar control films in conjunction with a daylight linked lighting control system; the lighting energy and cooling and heating loads were shown to decrease by 21.2% and 6.9%, respectively.

The amount of energy savings of daylight responsive dimming systems is difficult to accurately estimate because of many factors such as the proper position and calibration of their photosensors and their integration with shading systems. In particular, it is difficult to conduct studies to compare the energy performance of different systems due to a lack of methods for predicting energy savings [25]. Most previous studies have focused on measuring the available daylight and have mentioned the importance of predicting the indoor daylight illuminance [26,27]. Thus, many studies have calculated the amount of incoming daylight, but few studies have predicted the accurate lighting energy savings in these types of systems. Additionally, most previous studies on the methods used to predict the lighting energy savings of these types of systems used simulation tools and simple methods. Thus, an accurate verification method for predicted energy savings must be developed.

3. Experiment

3.1. Outline

As shown in Fig. 1, the experiments of this study were conducted in a space facing southwest with two windows (2400 mm × 1750 mm) that was divided into two spaces (i.e., the