Building and Environment 89 (2015) 229–243

Contents lists available at ScienceDirect

Building and Environment

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

Development of computational algorithm for prediction of photosensor signals in daylight conditions

Younju Yoon [a, 1], Ji-Hyun Lee [b, 2], Sooyoung Kim [c, *]

[a] Samsung C&T Corporation, Construction Technology Center, Seoul, South Korea
[b] Graduate School of Culture Technology, Korea Advanced Institute of Science and Technology, Daejeon, South Korea
[c] Department of Interior Architecture & Built Environment, Yonsei University, Seoul, South Korea

A R T I C L E I N F O

Article history:
Received 7 January 2015
Received in revised form
22 February 2015
Accepted 24 February 2015
Available online 5 March 2015

Keywords:
Photosensor signal
Lighting control
Daylight conditions
Shielding

A B S T R A C T

This study aims to develop and validate an annual photosensor performance simulation method (APPSM) to compute the photosensor signals for a lighting control system under various daylight conditions. A series of computer simulations using PSENS, which is a simulation program within Radiance software were conducted and field measurements were performed under various daylight conditions in order to validate the simulation results of APPSM.

Results indicate that the photosensor signals predicted by PSENS and APPSM showed a strong linear correlation. Prediction results by APPSM generally consisted with the results field measurements, although slight differences between them existed under particular daylight conditions. The differences in photosensor signals between the prediction by APPSM and measurement effectively decreased as shielding conditions were applied to photosensors.

A strong linear relationship existed between the photosensor signals obtained from prediction by APPSM and the field measurements. The prediction models for the photosensor shielding conditions were acceptable with a significance level of 0.01. The majority of percent differences between the measured and simulated photosensor signals were within 10% under clear and partly cloudy sky conditions.

1. Introduction

A daylight responsive dimming control system, which maintains a design level of illuminance at the task surface with the use of electric lighting, can significantly reduce the electric lighting use in spaces where daylight is a useful source of illumination [1–7]. Daylight associated with electric light which is controlled by a daylight dimming system contributes to occupants' visual comfort, psychological satisfaction and work productivity [8–15]. Despite the energy saving potentials and occupants' satisfaction obtained from the daylight dimming control system, it has not been widely used in commercial buildings due to the difficulty in the calibration and optimization of the system performance and malfunction of control system devices [16–19].

For the daylight dimming system, the ideal location for a photosensor would be on the workplane but this position is inappropriate because the photosensor would likely be disturbed or shaded by activities in the room. Thus, the photosensor is mounted on the ceiling rather than the workplane to minimize interference from activities in the room. Controlling workplane illuminance with a sensor located on the ceiling complicates photosensor control [20–25]. The correlation of the illuminance levels between the workplane and ceiling is strongly influenced by the position and spatial response of the photosensors [4,20,23,26–28].

Therefore, a proper calibration of a photosensor is critical to ensure reliable operation of lighting control system and lighting energy savings. In order to achieve a target light level at the workplane, the calibration of the photosensor for a particular sensor position and orientation for optimum operation adjusts the control algorithm, which is based on sensor signal to ballast output relationship [29–31].

* Corresponding author. Tel.: +82 2 2123 3142; fax: +82 2 313 3139.
E-mail addresses: younju.yoon@samsung.com (Y. Yoon), jihyunlee@kaist.ac.kr (J.-H. Lee), sooyoung@yonsei.ac.kr (S. Kim).
[1] Tel.: +82 10 9379 3371.
[2] Tel.: +82 42 350 2919.

http://dx.doi.org/10.1016/j.buildenv.2015.02.030

Nomenclature

ω_{sun}	solid angle of the sun
$\omega_{sky,patch}$	solid angle of the sky patch
$E_{ref,sun}$	reflected illuminance contribution from the sun
$DC_{ref,sky\ i}$	reflected component of daylight coefficient from sky patch i
L_{sun}	luminance of the sun
W_i	weighting factor for sky patch i

Knowing the annual performance of the photosensor is essential to determine an optimum sensor position and spatial response that influence lighting energy savings without undershooting or overshooting a target illuminance in space. Several computer simulation tools, such as SPOT, PSENS and DAYSIM, have been used to analyze photosensor system performance and the behavior of lighting control systems.

SPOT is used to simulate photosensor performance and determine optimum photosensor positioning using annual daylight performance in a space [32]. The annual daylight simulation is based on bihourly daylight factors for three representative days under clear and overcast sky conditions. The hourly computation of daylight performance is computed by interpolating pre-computed daylight factors. Accordingly, annual daylight performance is inaccurately estimated, especially for clear and partly cloudy sky conditions. In addition, the spatial distributions of the photosensors that control the influence of the photosensors on the dimming control system were not specifically included.

DAYSIM, which is based on Radiance, allows users to model annual variations of daylight in space and to analyze complex electric lighting systems controlled by a photosensor dimming system. Annual daylight simulation by DAYSIM is based on daylight coefficients approach and the Perez sky model [33–36]. Considering the spatial response of the photosensors and lighting control algorithms for the dimming and switching of the electric lighting system, the DAYSIM incorporates a separate module, which permits the analysis of electric lighting and the modeling of integrated photosensor lighting controls [37].

Also, it was known that the simulation error of DAYSIM expressed in mean bias errors (MBEs) ranged from 6 to 20% as compared to measured data [35,38]. However, the performance of the photosensor analysis module for calculations needs further validation against measured data under real daylight conditions.

PSENS, which is a simulation procedure within the Radiance software, is able to simulate the behavior of photosensors in response to various daylight and electric lighting conditions. Photosensor response is a function of the luminance distributions from all surfaces which are detected by the sensor. Therefore, it computes a photosensor signal by multiplying the luminance distribution of a space captured as a fisheye view with the angular sensitivity data of the photosensor.

The accuracy of the PSENS program in Radiance was validated with the percent error range of ±6.7% using measured data [39]. However, examining the annual performance of photosensors using PSENS is impractical since PSENS requires hourly fish-eye images of the space for an entire year, which is a very computationally extensive procedure. Accordingly, the performance of the photoelectric dimming control system simulated by PSENS was examined for limited photosensor conditions under various daylight conditions such as cloudiness levels.

Under these circumstances, an accurate annual photosensor performance simulation method, which computes photosensor signals considering its spatial sensitivity in response to various daylight conditions, are necessary in order to predict overall system performance prior to installation in the field and actual commissioning of photosensor-based lighting control system.

Therefore, this study develops an annual photosensor performance simulation method (APPSM) and validates its accuracy against an existing computation software and field measurement data. The photosensor signals computed with APPSM can be used to assist in the commissioning of photosensor-based lighting control system.

In this study, the theoretical foundation for the APPSM is proposed, and validations of computational results from the APPSM were performed in order to prove the accuracy of the computational results. The validation was performed by comparing the photosensor signals computed by APPSM with those predicted by the PSENS program in Radiance for typical classrooms, since PSENS is a validated program using field measurement data and proven to be accurate [38]. Also, the variations in illuminance computed by the APPSM were compared with actual data that were acquired in a full-scale mock-up space under a variety of sky conditions.

2. Development of computational algorithm

2.1. Computational algorithm for annual photosensor performance simulation method

The primary computational method developed in this study was the APPSM. The theoretical foundations that form the fundamental grounds for this method are briefly discussed in this section. The APPSM adopts the daylight coefficient theory and considers the sun and sky as separate light sources [40]. As shown in Fig. 1, the APPSM for the sky uses the daylight coefficients for the 145 sky patches covering the sky hemisphere to compute the illuminance contribution from each sky patch to an illuminance calculation point including interreflections [41].

This fixed numerical relationship between the luminance from the surface of each sky patch and the resulting illuminance at the calculation point is called a daylight coefficient. Once the daylight coefficients have been computed, the illuminance contribution from the sky with an arbitrary luminance distribution can be easily calculated by summing the multiplication of the luminance values of the 145 sky patches with their respective daylight coefficients. In this study, the daylight coefficients are computed using the *rtcontrib* program in Radiance, which traces rays from each analysis point and records the hits of individual sky patches until they reach the requested bounce numbers.

In the APPSM, the contribution from the sun is divided into direct and reflected components to achieve higher accuracy in the prediction of illuminance from the sun. The direct illuminance is calculated using *rtrace*, which is one of the computation programs in Radiance and takes only a few minutes to compute all hourly sun conditions occurring for an entire year. The reflected illuminance of the sun can be computed using the reflected daylight coefficients from the 145 sky patches, which have been computed to derive the illuminance contribution from the sky.

Two different approaches were considered to compute the reflected component of the daylight coefficient for a specific sun position [40,42,43]. One is to use the single-sky-patch condition. In this case, the reflected component of the daylight coefficient for the sky patch that contains the sun is used. For example, sky patch 132 shown in Fig. 2 has the sun at 11 a.m. on June 17 within the patch. Therefore, the reflected daylight coefficients from sky patch 132 are used to compute the reflected sun illuminance for the sun at 11 a.m. on June 17.