Solar Energy 153 (2017) 700–717

Contents lists available at ScienceDirect

Solar Energy

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

Accuracy analysis of computational algorithms for prediction of daylight illuminance in space with shading devices

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ARTICLE INFO

Article history:
Received 8 June 2016
Received in revised form 5 May 2017
Accepted 15 May 2017

Keywords:
Annual daylight simulation method
Daylight illuminance
Sky conditions
Radiance
Daylight coefficient approach
Sun-matching method

ABSTRACT

This study examines the accuracy of annual daylight simulation method (ADSM) in predicting illuminance for spaces with shading device conditions. ADSM algorithms were developed separately for the sun and sky to predict their effect on indoor daylight illuminance. Sun-matching and daylight coefficient methods were developed for the sun, while sky-matching and daylight coefficient methods with one and four sky patches were developed for the sky. The daylight illuminance computed from ADSM under various daylight conditions was compared with those calculated from Radiance and field measurements.

Results imply strong linear correlations existed between the predicted daylight illuminance levels by the ADSM and Radiance under diverse sky conditions based on weather data. The predicted illuminance from ADSM was lower than field measurements for all sky conditions. ADSM computations mostly agree with field measurements. For clear and partly cloudy sky conditions, the daylight coefficient approach for sky of ADSM generated a stronger correlation to measured data, but the sky-matching algorithm showed a stronger correlation to field data. The daylight coefficient approach for sky, combined with ADSM computation algorithms for sun, effectively reduced the difference between the predicted and measured illuminance under clear or partly cloudy sky conditions. Under overcast conditions, there was no significant reduction in difference between simulated and measured illuminance.

1. Introduction

Energy is consumed in buildings to maintain the indoor environment comfortable for the occupants. Buildings take up 41% of the total energy consumed in a country (D&R International Ltd., 2012). In particular, residential and commercial buildings account for 54% and 46%, respectively. In addition, electric lighting energy constitutes 9% of the energy consumption in buildings.

The introduction of daylight to building interiors has the potential to enhance the quality of the environment while providing opportunities to save energy and reduce greenhouse gases by displacing or supplementing electric lighting. The use of daylight helps to reduce heating and cooling loads, which offers additional energy saving opportunities as well as reductions in heating, ventilation, and air conditioning equipment sizing and initial cost (Papamichael et al., 1998).

However, improper selection or design of window systems may negate the benefits of electric lighting energy reduction by increasing requirements for air conditioning and degrading the quality of visual environment. Accordingly, appropriate designs and selections of window systems with shading devices should be applied.

To compare the effectiveness of different window systems, simulations based on hourly local weather data need to be performed to estimate the annual daylight availability and total building energy consumption. Accurate simulation of annual daylight availability, coupled with the building thermal simulations, provides the most reliable estimation of electric lighting energy consumption and results in more accurate calculations of cooling and heating energy demands (Guglielmetti et al., 2010).

Thus, successful designs or selections of energy-efficient daylight systems considering all factors that influence energy performance of buildings can be achieved. Accurate estimation of annual daylight availability is achieved by performing a series of daylight simulations for hourly or subhourly annual daylight conditions (Winkelmann, 2002). Hourly daylight simulation for a year is computationally very expensive, thus selective simulations for

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http://dx.doi.org/10.1016/j.solener.2017.05.048
0038-092X/

Nomenclature

ω_{sun}	solid angle of the sun [sr]
$\omega_{sky,patch}$	solid angle of a sky patch [sr]
$E_{ref,sun}$	inter-reflected illuminance contribution from the sun [lx]
$DC_{ref,sky\,i}$	inter-reflected component of daylight coefficient from sky patch i
L_{sun}	luminance of the sun [cd/m^2]
$W_{sky,i}$	weighting factor for sky patch i
$W_{sun,i}$	weighting factor for sun i
$E_{sun,test\,date}$	illuminance from the sun on a test date [lx]
$E_{rep.\,sun,i}$	illuminance from the representative sun i [lx]
$SolarRadiance_i$	solar radiance for the representative sun i [W/m^2/sr]
$SolarRadiance_{test\,date}$	solar radiance for test date [W/m^2/sr]

representative hours of the year are usually performed for annual daylight availability simulation (Architectural Energy Corporation, 2006). Fast, yet accurate annual daylight simulation method considering all hourly daylight conditions needs to be developed.

Windows introduce daylight into a space and admit solar radiation, which increases cooling energy demands and risk of thermal discomfort. Daylight systems, which simultaneously control the thermal and visual environment, should be installed to prevent excessive solar heat gain and direct sunlight. Most daylight simulation programs are used to identify suitable shading and redirection devices and control strategies (Reinhart and Friz, 2005). Shading devices, especially blinds, have variable light and solar heat transmission characteristics depending on the incoming and outgoing direction of light. Moreover, blinds significantly influence the performance of a photosensor-based daylight dimming system. The tilt angle of the blind slats changes the ratio of a photosensor signal to workplane illuminance and affects the ability of the system to maintain the target illuminance level (Lee et al., 1999; Rubinstein et al., 1998).

Most annual daylight simulation tools did not accurately model the blinds geometry and assumed a constant transmittance value for the inclusion of blinds until the daylight coefficient approach was adopted as an efficient algorithm for annual daylight simulation (Reinhart, 2005). In this approach, the daylight coefficient is defined as the contribution of a sky patch to the total illuminance at a point in a building, assuming that the hemispherical sky is divided into disjoint sky patches (Tregenza and Waters, 1983). The introduction of the daylight coefficient approach enabled annual daylight simulation at hourly or subhourly time steps with reasonable computation time and accuracy for windows with or without a daylight system (Janak and Macdonald, 1999; Mardaljevic, 1999; Reinhart and Herkel, 2000). DAYSIM is an example of a tool that implements the daylight coefficient approach to estimate the annual daylight level and the lighting energy savings using window systems with blinds (Reinhart, 2005).

To effectively compute the annual daylight availability for a complex fenestration system, Radiance incorporated a three-phase model, which computes the daylight contribution in three steps: (1) sky to exterior fenestration, (2) fenestration transmission, and (3) fenestration to the simulation space. Measured or computed bidirectional scattering distribution functions (BSDFs) of complex window systems such as blinds are considered instead of modeling the geometry of system (McNeil, 2014).

The three-phase model, which follows the standard daylight coefficient model for dynamic daylight simulations, enhanced the accuracy by separately computing direct solar components from the inter-reflected solar component (Bourgeois et al., 2008; McNeil, 2013). This model provided a mean bias error below 13% and a root mean square error below 23%, compared to the measured illuminance levels for a test office equipped with an innovative daylight system (McNeil and Lee, 2012).

The accurate simulation of the annual performance of complex fenestration systems can be achieved if BSDF data for daylighting, shading, and fenestration systems are available. With the Window 5 software, BSDF data are much easier to obtain than before, but still, in many cases, such data are not easily available for glazing, which is mostly used for buildings. Additionally, a simple and easy method is necessary for the estimation of annual daylight availability (Mitchwell et al., 2001).

Therefore, this study develops annual daylight simulations methods (ADSM) and examines the accuracy of ADSM in predicting illuminance with shading devices. The ADSM was developed theoretically and the illuminance calculations using the ADSM were conducted separately for the sun and sky. The prediction accuracy of the ADSM was tested through comparison of an hourly illuminance output from Radiance simulations and field measurement data under actual diverse daylight conditions.

2. Development of prediction method

In this study, annual daylight simulation algorithms were developed separately for the sun and the sky in order to predict the effect of sun and sky to indoor daylight illuminance. For the sun, the sun-matching method and daylight coefficient methods with one and four sky patches were developed theoretically. And, the sky-matching and daylight coefficient method were developed for the sky. The five computation algorithms were used to compute the total daylight illuminance at calculation points in space.

For the computation algorithm, the one or four sky patches was used to derive the reflected solar illuminance from the reflected illuminance contribution from the sky. Single sky patch was used because it contains the sun. However, the sun may not be at the center of the sky patch but at one corner where a neighboring sky patch can be closer to the sun. Therefore, neighboring four sky patches was also used.

Among the ADSMs, the daylight coefficient approach developed in this study uses daylight coefficients computed using Radiance. The daylight coefficient method computes daylight coefficients separately for the sky and the sun. The method differs from the three-phase and five phase method used for Radiance. The three-phase method computes sky and solar contributions concurrently and the five phase method conducts separate addition of direct solar contribution for better accuracy.

Compared to the five-phase method of Radiance, the daylight coefficient approach developed in this study uses a different number of direct sun positions in the simulation. The five-phase uses 5,185 sun positions located at the center of 5,185 subdivided sky patches, whereas the approach used in this study uses actual sun positions that can vary in number depending on the time simulated. For example, if the direct solar illuminance is computed on an hourly basis from 8:00 to 17:00 for a year, the total simulation case is 3,650 (10 sun positions per day multiplied by 365 days). Also, the three-phase and five-phase methods compute the