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Development of a New Framework for Daylighting Simulation with Dynamic Shading Devices

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ABSTRACT

Daylight plays an important role in building design. It affects occupant's activities, reduces energy demand, and supports human health. However, most daylighting simulation software does not capture the behaviors of occupants and of dynamic shading. DAYSIM is the only simulation software that calculates dynamic shading devices using a lightswitch model, but it has limitations. It is unable to use other automated control algorithms or capture occupant's behavior. It is also unable to simulate advanced shading devices that can only be described by a bidirectional scattering distribution function, such as light redirecting films.

In this paper, a new framework is developed based on three-phase method in Radiance to enable an accurate annual daylighting simulation in a room equipped with dynamic shading devices and/or daylight redirecting devices. Two case studies are carried out using the Hanoi climate to demonstrate the capability of the framework. The framework can flexibly run any automated control algorithms and any dynamic behaviors by occupants, which allow future smart building applications. In the future, the framework will be expanded to run five-phase method in Radiance and a user-friendly interface will also be developed.

1. INTRODUCTION

A shading device is one of the main components designed not only to block direct sunlight but also to redirect daylight. Well-designed shading devices can significantly decrease the amount of energy spent to cool and promote daylight utilization in buildings. Shading devices can also be used to prevent glare by reducing contrast ratios in a building interior. There are various shading strategies on using different shading devices such as fixed shading devices, dynamic shading devices, interior shading devices, and exterior shading devices or using light redirecting devices such as light shelves and light redirecting film. However, most simulation software only captures daylighting for the room equipped with fixed shading devices.

DAYSIM is the only program that calculates annual illuminance results for every state of shading devices which uses a lightswitch model to calculate in which state the shading systems are going to be (Reinhart, 2018). The lightswitch model is a manual lighting control model predicting the use of dynamic shading devices and the use of artificial lighting based on user occupancy, annual daylight results, and user-dependent switching probabilities in an office (Reinhart, 2001). The limitations of DAYSIM, however, are that it only follows the lightswitch model, is unable to use other automated control algorithms or other occupants' behavior model, and is unable to simulate advanced shading devices that can only be described by a bidirectional scattering distribution function (BSDF), such as light redirecting devices. The occupants' behavior has a significant impact on building energy use and is one of the major sources of uncertainty in the prediction of building energy use by simulation programs (Hong & Lin, 2012).

This study develops a new framework to calculate annual illuminance in a room equipped with dynamic shading devices and/or daylight redirecting devices, as well as a shade control strategy. Based on illuminance results, daylight metrics are plotted to evaluate daylight autonomy (DA), spatial daylight autonomy (sDA), simplified daylight glare probability (DGPs), etc.

2. LITERATURE REVIEW

2.1 Daylight metrics

Historically, many daylight metrics have been investigated to evaluate daylight performance in building. They are divided into static daylight metrics and dynamic daylight metrics.

Daylight autonomy (DA), is a dynamic daylight metric, is defined as a percentage of annual daytime hours that is lighted above an illuminance threshold at a given point on a floor area (Reinhart & Walkenhorst, 2001). Continuous daylight autonomy (cDA) is based on DA and cDA accepts partial credit at the point lighted under an illuminance threshold (Rogers & Goldman, 2006). In this study, we also evaluate spatial daylight autonomy (sDA) which is a percentage of floor area that receives more than or equal to 300 lux for at least 50% during standard working hours (8:00 am – 6:00 pm) (IESNA, 2012).

Glare is a subjective human sensation perceived in a visual field brighter than the brightness to which the eyes can adapt. The daylight glare probability (DGP) is the most suitable metric to assess glare compared to the daylight glare index, visual comfort probability and unified glare rating (Jakubiec & Reinhart, 2011). It is often simulated using the Evalglare tool in Radiance (Wienold, 2004). To decrease the gap between simulation and reality, the DGP was investigated based on vertical illuminance at eye level (Wienold & Christoffersen, 2006). DGP is determined by:

$$\text{DGP} = 5.87 \times 10^{-5} \times E_V + 9.18 \times 10^{-2} \times \log_{10}(1 + \sum_i \frac{L_{S,i}^2 \times \omega_{s,i}}{E_v^{1.87} \times P_i^2}) + 0.16 \tag{1}$$

where E_V is the vertical illuminance at eye level [lux], L_s is luminance of source [cd/m^2], ω_s is solid angle of source [sr], and P is the position index [-]. As the DGP requires a significant amount of time and disk space to generate pictures for each time step, the DGPs was developed to make glare prediction faster (Wienold, 2007). The DGPs is defined as:

$$\text{DGPs} = 6.22 \times 10^{-5} \times E_V + 0.184 \tag{2}$$

where E_V is the vertical illuminance at eye level, in lux. The DGPs is considered in this study, although it can only be applied if no direct sunlight or specular reflection of it hits the eye of the observer.

2.2 Shading control

The purpose of shading control is to block excessive sunlight and to allow diffuse light into the working space, thereby preventing glare and reducing overheating and lighting energy consumption. In this study, two types of shading control algorithms are used to demonstrate the ability of the developed framework: work plane protection control and work plane protection considering weather. Work plane protection control (or using a control reference point) is a method used to block direct sunlight influencing a work plane by changing a shade's position. Figure 1 illustrates the roller shade length relative to the position of a control reference point.
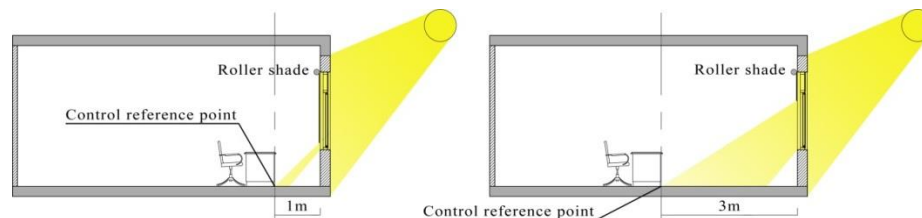

Figure 1: Correlation between the control reference point and shade length.

According to Chan (2015), the shade position is proportionally controlled and determined by:

$$H_{so} = D_w \times \tan(\Omega) \text{ and} \tag{3}$$
$$h_{wp} = (H + D_{fw}) - H_{so} \tag{4}$$

where H_{so} is the shade opening's height relative to the floor [m], D_w is the distance from the window to the working area [m], Ω is the profile angle of the Sun [^{o}], H is the window height [m], D_{fw} is the distance from the window to floor [m], and h_{wp} is the shade length calculated from the work plane protection algorithm [m].

The weather is considered by an indoor sensor point near the window to represent transmitted illuminance. Shade length is determined by using work plane protection control if the transmitted illuminance is in the comfort range. The shade is fully opened if the illuminance at the sensor point is less than 4000 lux and is fully closed if it exceeds 30,000 lux.

2.3 Solar angle

The solar angles are calculated using the following equations based on the local latitude (λ), local longitude (L_{loc}), time zone (L_{st}), local standard time (t_{loc}), surface azimuth (ψ), and surface tilt (β). The profile angle (Figure 2) is the angle between a line perpendicular to the plane of the window and the rays of the Sun perpendicular to the window plane. It helps us to investigate the optimal length of shading device dealing with sunlight.
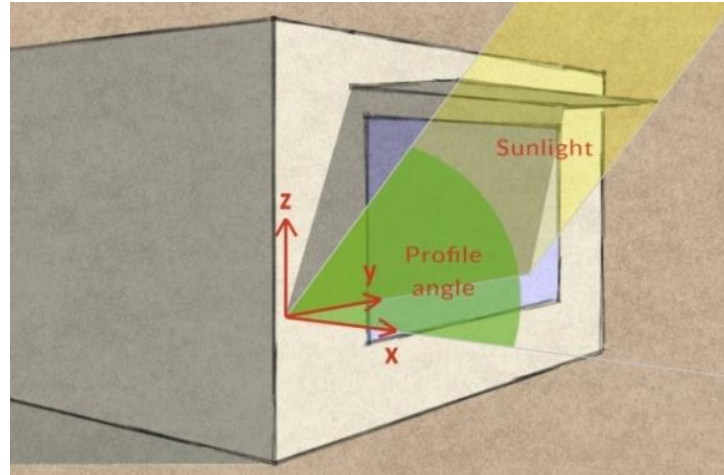

Figure 2: Profile angle.

The equation of time is the difference between the mean solar time (as shown by clocks) and the apparent solar time (as indicated by sundials), which varies with the time of year. It is determined by:

$$E_{t(n)} = \left[9.87 \times \sin\left(2\frac{360(n-81)}{364} \right) - 7.53 \times \cos\left(\frac{360(n-81)}{364} \right) - 1.5 \times \sin\left(\frac{360(n-81)}{364} \right) \right]. \tag{5}$$

Solar time is based on the apparent angular motion of the Sun across the sky, with solar noon being the time that the Sun crosses the meridian of the observer. It is determined by:

$$t_{sol} = t_{loc} - (L_{st} - L_{loc})/15 + {}^{E_t}/_{60}. \tag{6}$$

Solar declination is the angular position of the Sun at solar noon with respect to the equatorial plane. It is determined by:

$$\delta = 23.45 \times \sin\left(360 \times \frac{284+n}{365} \right). \tag{7}$$

The solar hour angle is an expression of time, expressed as an angular measurement usually in degrees, from solar noon. The solar hour angle is determined by:

$$\omega = (t_{sol} - 12) \times 15. \tag{8}$$

The solar altitude is the angle of the Sun relative to the Earth's horizon and is determined by:

$$\alpha = \sin^{-1}(\cos(\lambda) \times \cos(\delta) \times \cos(\omega) + \sin(\lambda) \times \sin(\delta)). \tag{9}$$

The surface solar azimuth is the angle between the horizontal projection of the Sun's rays and the surface azimuth. It is determined by:

$$\gamma = |\varphi - \psi|. \tag{10}$$

The solar azimuth is the angle between the horizontal projection of the Sun's rays and due south. It is determined by:

$$\varphi = \cos^{-1}\left(\frac{\sin(\alpha) \times \sin(\lambda) - \sin(\delta)}{\cos(\alpha) \times \cos(\lambda)} \right) \times \frac{\omega}{|\omega|}. \tag{11}$$

The angle of incidence is the angle between the solar rays and a line normal to the surface and is determined by:

$$\theta = \cos^{-1}(\cos(\alpha) \times \cos(\gamma) \times \sin(\beta) + \sin(\alpha) \times \cos(\beta)). \tag{12}$$

The profile angle is the vertical angle from the horizon of the Sun projected onto building surfaces and is determined by:

$$\Omega = \tan^{-1}\left(\frac{\tan(\alpha)}{\cos(\varphi-\psi)} \right). \tag{13}$$

3. METHODOLOGY

3.1 Framework
The framework is a chain of running three-phase method in Radiance and combining illuminance with a dynamic shading device and a shading control in order to calculate and visualize daylighting metrics from a 3D model and a weather data. It is described in Figure 3. For simulating dynamic shading devices, we build the model with each shade state and evaluate those models separately before collecting the optimal shade state. Daylight redirecting devices are defined in xml files and are simulated using the three-phase method in Radiance.
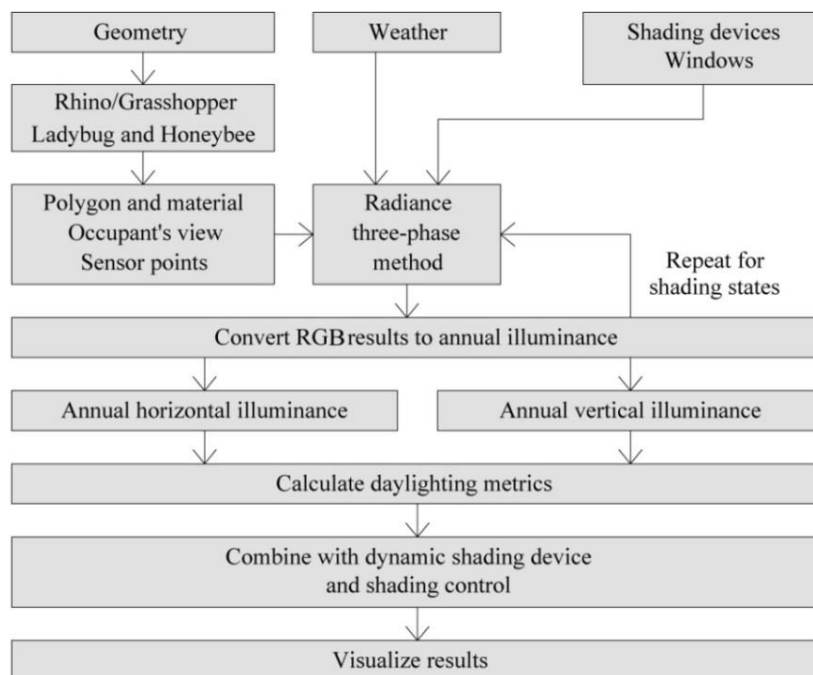

Figure 3: Simulation framework.

The geometry, materials, occupants' view, and sensor points can be defined using 3D Rhinoceros software (Robert McNeel & Associates, 2018) in combination with the parametric plug-in Grasshopper (Robert McNeel & Associates, 2018), and Ladybug & Honeybee (Roudsari, 2018). The three-phase method in Radiance (McNeil, 2014) requires the xml files of the fenestration system that can be generated using LBNL's WINDOW software (Lawrence Berkeley National Laboratory, 2018). RGB results are computed using Radiance based on a weather file. Finally, we visualize the results, such as cDA and DGPs in temporal graphs.

3.2 Model input
Grasshopper is a "graphical algorithm editor" plugin for Rhino. Ladybug and Honeybee are designed for environmental analysis in Grasshopper based on standard EnergyPlus Weather files. Ladybug automates and expedites the calculations and simplifies the simulation process. It also allows users work with validated engines such as EnergyPlus, Radiance and DAYSIM. Similar to Ladybug, Honeybee is designed to run the analysis on building masses but for more advanced studies (Roudsari, Pak, & Smith, 2013).

Rhino, Grasshopper, Ladybug and Honeybee are used to generate material files, polygon files, occupant view files, and sensor point files for every shade state. They convert a 3D model to a rad file storing the coordinates of the main points in the model. Honeybee supplies some default and optional Radiance materials and generates sensor points for daylight simulation. An occupant view is determined using Ladybug.
To conduct the three-phase method, the files generated by Ladybug and Honeybee need to be revised to fit into the three phase method's simulation scheme. First of all, a material file and a polygon file are generated by Honeybee. The shading device and window data in those files need to be moved to the new files. Then, the material types of the shading devices and the glass set by Honeybee are changed to "glow" in order to create a glow source on the window. LBNL's WINDOW software will generate the materials of the shading device and window in an xml type.

Figure 4 (left) shows a roller file containing the "glow" material and a polygon of a roller shade model. Then, a ground file is created as an example in Figure 4 (right).
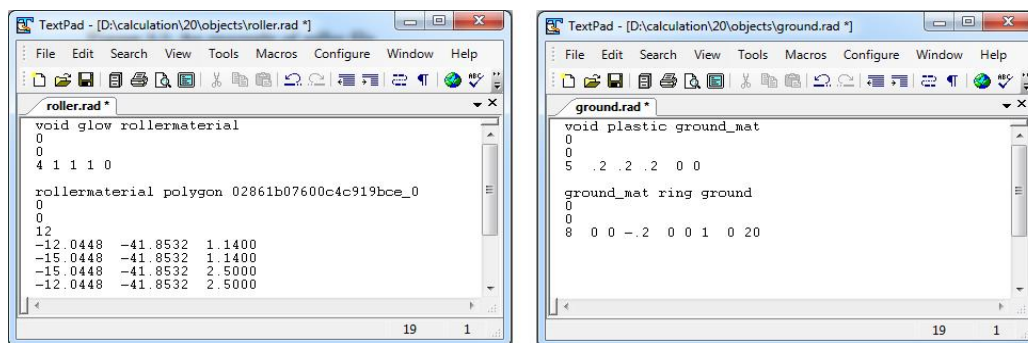

Figure 4: An example of the roller file (left) and ground file (right).

3.3 The three-phase method in Radiance
The three-phase method divides the light path into three parts to compute. The light between the fenestration system and sensor points is simulated using "rcontrib" tool and "klems_full.cal" tool. The "klems_full.cal" file contains equations that allow "rcontrib" to generate rays hitting the window based on their incident direction. To calculate the light transmission through the fenestration system, Radiance uses the front transmission data of the fenestration system in the BSDF file (xml type). Evaluating the fenestration system in BSDF file is a remarkable development in the three-phase method compared to traditional method in Radiance. It enables an accurate annual daylighting simulation in a room equipped with daylight redirecting devices. Finally, exterior transport occurs from the sky divisions to the window's incident Klems divisions. The "genklemsamp" tool is used to sample the incident Klems directions for a window for daylight contributions. Sample rays produced by "genklemsamp" are passed directly to "rcontrib" to compute the contribution coefficients from the sky divisions.

The three-phase method is run again for all shade states defined in the 3D model. Thus, we determine the indoor daylight availability for every shade state at each time interval under a weather data for a year. In the case study, we run eleven times to capture eleven shade states for the window including low-e glass and roller shade. Thereafter, two result files are generated for each state of the roller shade. One file represents the annual daylighting transmitted through the roller shade in RGB and the other represents the annual daylighting transmitted through low-e glass in RGB. Those files are then combined and converted from the RGB results to illuminance results.

3.4 Shading control
The Sun shining down directly on a working plane causes visual discomfort. To ignore this issue, we first determine profile angles using equation (13) based on the geographic location of the model. The shade positions for 8760 hours in a year (from January 1st 01:00 to December 31st 24:00) are then calculated using Equation (4). It represents a case with a shading control algorithm which prevents direct sunlight falling on the work plane. We also can add one sensor point near the window to detect the indirect sunlight too high or too low. For each shade position, we categorize which shade state it belongs. Then we look up the result file from categorized states and combine them as the final annual results.

In the case study, the distance between the window and the work plane is set a 1 m and 3 m. Case 1 only considers preventing direct sunlight on the work plane. It consists of two terms: profile angle (equations (5)-(13)) and shade length (equation (3) and (4)). The shade length results are calculated for 8760 hours. Each shade length determines illuminance results for a corresponding shade length modeled using the three-phase method in Radiance. The roller shade control in case 2 is similar to that in case 1. In addition, the weather is considered before the Sun's position. The sensor point is 1 cm from the window, and is used to determine whether the roller shade should open fully if the illuminance is less than 4000 lux or if it should close fully if the illuminance is more than 30,000 lux.

3.5 Daylight metrics
Daylight metrics show a fast and accurate evaluation for daylight availability in a room compared to the numbers in illuminance results. Each metric shows a different aspect of daylight performance. We can flexibly calculate and visualize daylight metrics depend on what we need.

4. CASE STUDY

Two test cases are conducted in order to demonstrate the ability of developed framework. Two performance categories for daylight − work plane illuminance and discomfort glare − are evaluated using a series of daylight metrics namely DA, cDA, sDA, average cDA and DGPs. The simulation still considers automated shading control algorithms.

4.1 Office room model
The model is an office room located in Hanoi, Vietnam. The south façade is divided into a spandrel, window (low-e glass and roller shade) and wall. In working hours, occupants fully open the roller shade or change its height (the roller shade closes from 0% to 100% in eleven states) to satisfy their required visual performance and comfort. Two test cases (Table 1) are evaluated to demonstrate the efficiency of this framework.

Table 1: Summary of modeling assumptions.

	Case 1	Case 2
Shading control	Consider Sun's position	Consider Sun's position and weather
Location	Hanoi	
Room dimensions	3 m wide, 7 m deep and 3.3 m high	
Floor area	21 m^2	
Reflection of indoor surfaces	Walls: 0.5; floor: 0.2; ceiling: 0.8; spandrel: 0.6	
Reflection of roller shade	0.4209	
Glass material	Tvis = 0.679 U-value = 1.654 W/m^{2}K SHGC = 0.377	
Ground reflection	0.2	
Obstructions (buildings, trees, etc.)	None	
Window-to-wall area ratio	51%	
Façade orientation	South	
Distance from window to working area	Two cases: 1 m and 3 m	
Illuminance threshold for calculating DA, cDA and average cDA	500 lux (according to IESNA requirements)	
Illuminance threshold for calculating sDA	300 lux (IESNA, 2012)	
Working hours	8:00 am – 6:00 pm	
Simulation timestep	1 hour	

4.2 Daylighting availability evaluation
The DA and cDA are used to calculate the percentage of annual working hours that is lighted more than or equal to 500 lux at each sensor point at 0.85 m above the floor of the model. The cDA also considers the daylight availability at a sensor point receiving less than 500 lux.

Figures 5 and 6 show the DA for the two cases in the Hanoi climate. The DA for case 1 (3 m) is significantly higher than the DA for case 1 (1 m). The DA for case 2 (3 m) is slightly higher than the DA for case 2 (1 m), especially for the area near the window.

It can be easily seen that the distribution of daylight in the model for case 1 (3 m) and for case 2 (3 m) is better than that for case 1 (1 m) and case 2 (1 m), because the distance between the work plane and window in case 1 (1 m) and case 2 (1 m) is shorter than that in case 2 (3 m) and case 2 (3 m). When calculating shading height, using 3 m as a reference will always yield a shorter shade and make the room brighter. Therefore, when implementing lighting control in practice, the reference point should be carefully selected. The next section will discuss the issue of glare; if no one is sitting inside the buffer zone (the distance between the reference point and window), then the daylight availability can be increased without disturbing occupants. However, if someone is sitting inside the buffer zone, then glare issue should be carefully examined.

The DA for case 2 (1 m) is slightly higher than the DA for case 1 (1 m) at sensor points near the window. In contrast, the DA for case 1 (3 m) is higher than the DA for case 2 (3 m). This shows that the intensity of daylight

near the window in case 1 (3 m) is very high across the whole year; as a result, visual discomfort and thermal discomfort might occur.
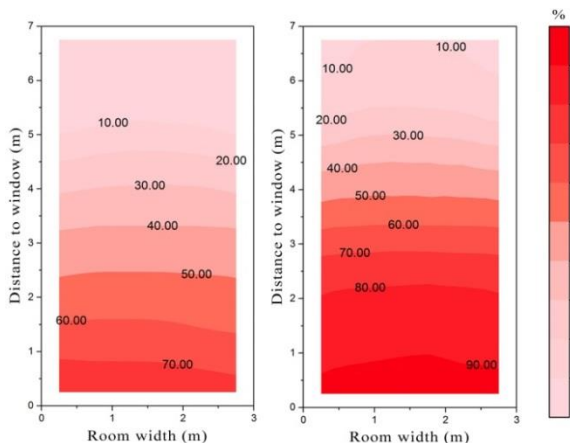

Figure 5: DA distributions for Case 1, with control reference points at 1 m (left) and 3 m (right) from the window.
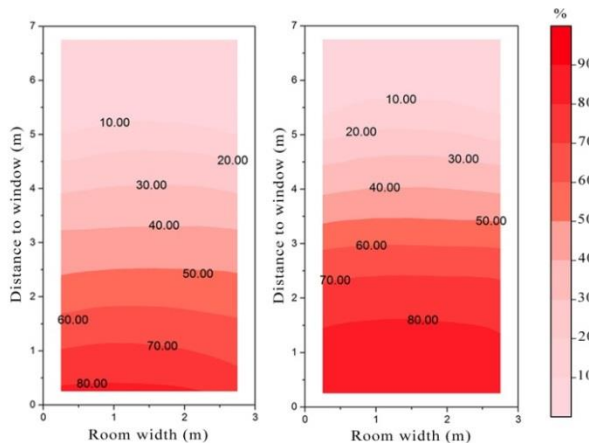

Figure 6: DA distributions for Case 2, with control reference points at 1 m (left) and 3 m (right) from the window.
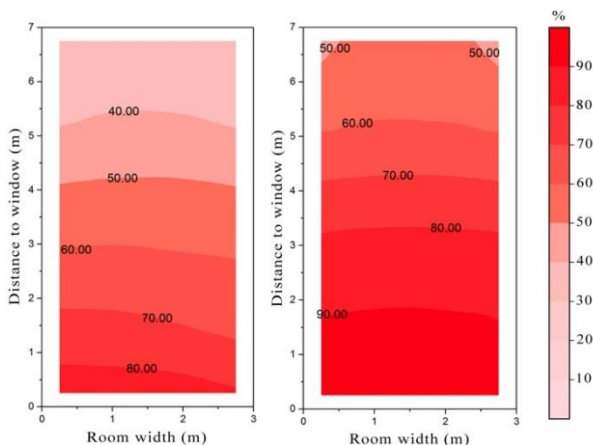

Figure 7: cDA distributions for Case 1, with control reference points at 1 m (left) and 3 m (right) from the window.
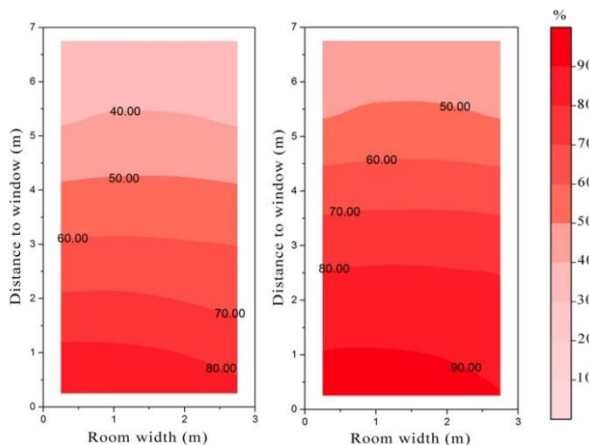

Figure 8: cDA distributions for Case 2, with control reference points at 1 m (left) and 3 m (right) from the window.

Figures 7 and 8 show the cDA distributions for the two cases. In general, the correlations between case 1 (1 m), case 1 (3 m), case 2 (1 m), and case 2 (3 m) assessed via the cDA are similar to those assessed via the DA. The areas for each daylighting level are extended and the lowest daylighting level are 30% (case 1 (1 m) and case 2 (1 m)), 40% (case 2 (3 m)) and 50% (case 1 (3 m)). The sDA for case 1 (3 m) indicates that the total daylight availability of the model across the whole year is sufficient, although the illuminance does not reach 500 lux in some time intervals. Therefore, the energy utilized for additional artificial lighting is not significant.

Table 2 shows the sDA and average cDA values for the two cases. The daylight metrics in case 1 are similar to those in case 2 for the control reference point at 1 m from the window. However, the daylight metrics in case 1 are better than those in case 2 for the control reference point at 3 m from the window.

Table 2: sDA and average cDA results for the two cases.

	Case 1		Case 2	
Distance between control reference point and window	1 m	3 m	1 m	3 m
Spatial daylight autonomy	50%	71%	50%	64%
Average continuous daylight autonomy	56%	75%	57%	69%

4.3 Discomfort glare

Figures 9 and 14 illustrate the DGPs metrics used to determine visual comfort classes for the two cases. For the cases with the DGPs sensor point at 6 m from the window, there were no hours when there was visual discomfort. With the DGPs sensor point at 3 m from the window, discomfort from glare occurring in the winter months was greater than that in the summer months for case 1 (1 m and 3 m) and case 2 (1 m and 3 m). However, discomfort from glare is significantly reduced in the winter months when there was shading control considering both the Sun's position and the weather. With the DGPs sensor point at 1 m from the window, an intolerable degree of glare occurs across most of the year in case 1 (1 m). Visual discomfort is decreased significantly in February and March because the amount of hours of sunshine in Hanoi is lowest in that period.
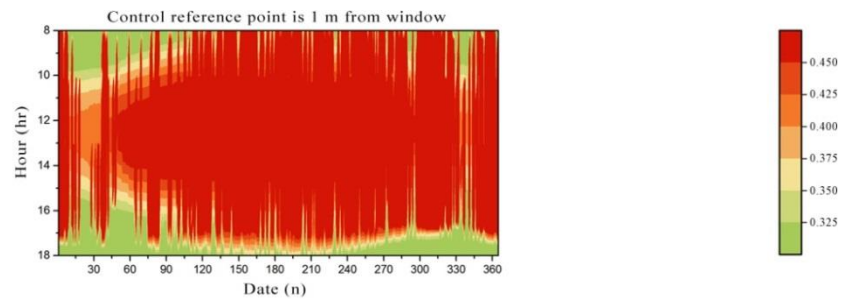

Figure 9: Case 1 with the DGPs sensor point at 1 m from the window.
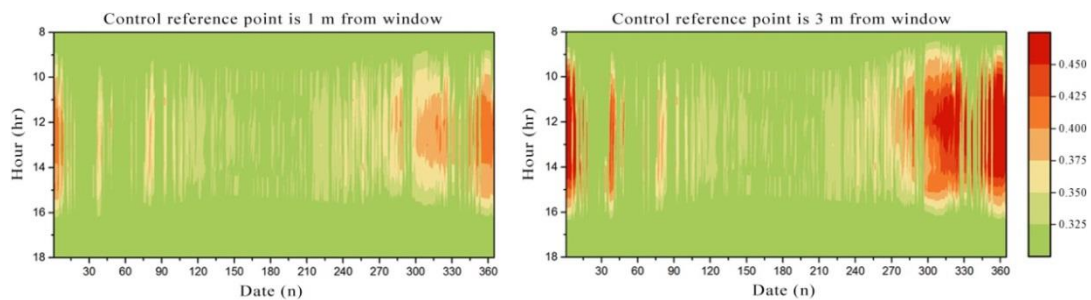

Figure 10: Case 1 with the DGPs sensor point at 3 m from the window.
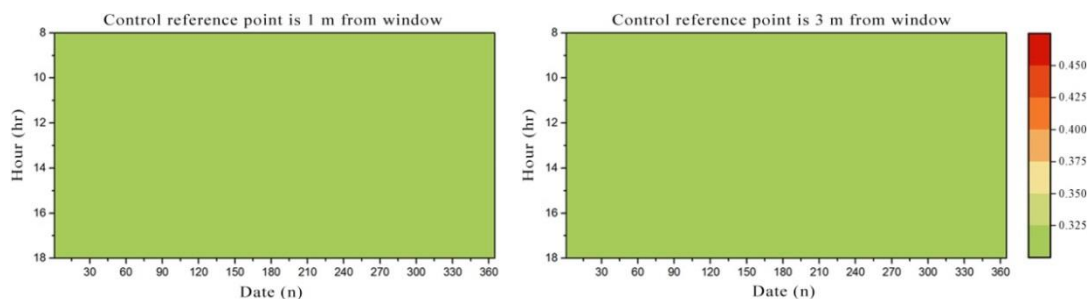

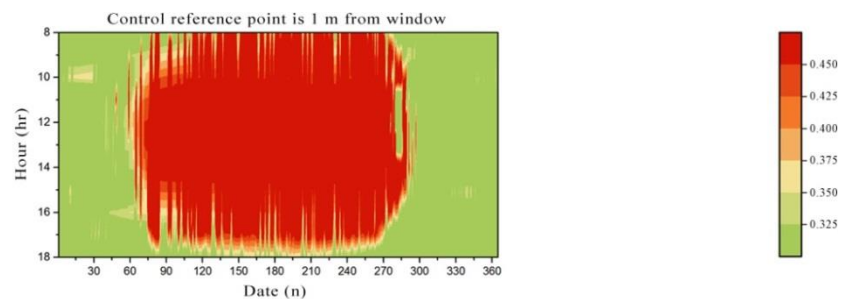**Figure 11:** Case 1 with the DGPs sensor point at 6 m from the window.

Figure 12: Case 2 with the DGPs sensor point at 1 m from the window.
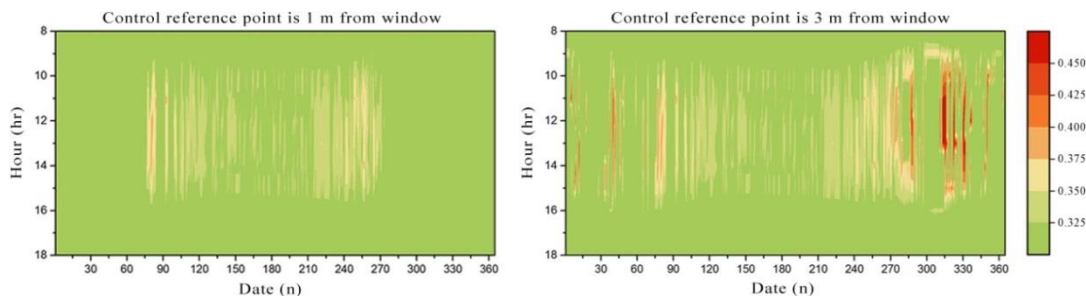
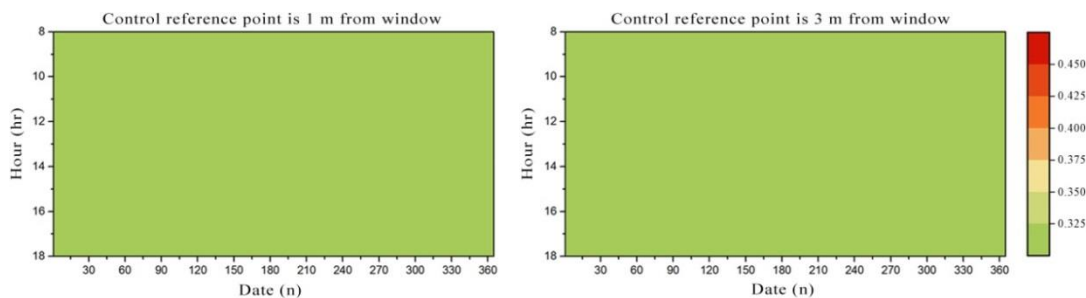**Figure 13:** Case 2 with the DGPs sensor point at 3 m from the window.

Figure 14: Case 2 with the DGPs sensor point at 6 m from window.

When the Sun's position and the weather are both considered, an imperceptible degree of glare is stable in the first two months and in the last three months, but visual discomfort changes slightly mid-year.

4.4 Summary

Two case studies were carried out in the Hanoi climate in order to demonstrate the capability of the developed framework. The daylight availability results for a control reference point at 1 m in the two cases were slightly different while the daylight availability results for a control reference point at 3 m were largest for case 1. The daylight metrics for the model with a mounted roller shade controlled by the Sun's position show a uniform distribution of daylight. Visual comfort is better when the shade is controlled considering both the Sun's position and weather, while the daylight availability is slightly reduced. Shade control considering the Sun's position reduced the glare significantly for both two cases with DGPs sensor points at 3 m and 6 m from the window. For case 1 with a DGPs sensor point at 1 m, an intolerable degree of glare frequently occurs across whole year. When the shade control considers both the Sun's position and weather, visual comfort is improved, although it is nearly unchanged in summer months. Moreover, the DGPs calculation is remarkably faster than the DGP calculation.

5. DISCUSSION AND CONCLUSIONS

This study provided a new framework for daylighting simulation that can be used to assess and compare daylight availability, as well as visual comfort, with the goal of delivering maximum daylight over the course of the year. In order to maximize daylighting in buildings, dynamic shading devices are controlled by the Sun's position, combined with local weather.

This new framework has the ability to simulate not only fixed and dynamic shading devices, but also light redirecting devices. The three-phase method in Radiance uses a backward ray-tracing algorithm to simulate annual illuminance and the front transmission data of a fenestration system in a BSDF file to compute the light transmission through the fenestration system. The framework developed based on the three-phase method is capable of accurate annual daylighting simulation in an office room equipped with daylight redirecting devices. Moreover, it generates indoor illuminance profiles for every state of dynamic shading devices and combines those results with shading control, which can be used for automatic control or smart buildings.

Glare is an important parameter in predicting occupants' behavior. It is often simulated using the Evalglare tool in Radiance and showed as DGP metric. Although DGP can be simulated in this framework, using DGPs to evaluate is faster because the HDR simulation for computing DGP is time consuming.

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