

Development of a Fast and Accurate Daylighting Simulation Approach

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ABSTRACT:

The introduction of daylight through window systems to building interiors has the potential to save electric lighting energy and heating and cooling loads. Therefore, combined lighting and building thermal energy simulations based on hourly local weather data must be performed to estimate accurate total building energy use. This paper develops a fast and accurate annual daylight simulation approach for spaces with daylight systems and exterior obstructions can be performed. To compute the illuminance contribution from the sky and the sun, a daylight coefficient approach were studied. The proposed annual daylight simulation method consumes much less computation times required for the sun and sky annual daylight simulations, respectively, using the standard RADIANCE rtrace method.

Keywords: Annual daylight simulation, daylight coefficient, Radiance, exterior obstructions, Lighting

1.INTRODUCTION

In this paper, the sun and the sky are treated as separate light sources. The proposed approaches for the sky illuminance calculation include: i) a daylight coefficient approach. Methods for computing the illuminance from the sun involve: i) a sun matching method, and ii) a daylight coefficient approach. Simulation cases are applied to test the performance of these suggested methods.

2. DAYLIGHT COEFFICIENT APPROACH

The daylight coefficient approach was developed by Tregenza and Waters (1983). If a single sky patch at altitude γ and azimuth α with luminance of L provides

illuminance, $E_{\gamma,\alpha}$, at a measurement point, the daylight coefficient is defined as follows (Mardaljevic 1999) (see Eq. 1).

$$D_{\gamma\alpha} = \frac{E_{\gamma\alpha}}{L_{\gamma\alpha} \Delta\omega_{\gamma\alpha}} \quad \text{Eq. 1}$$

Where, $\Delta\omega_{\gamma\alpha}$ = solid angle of the sky patch in Figure 1.

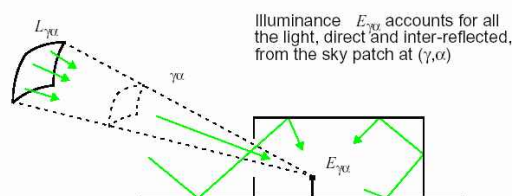


Figure 1 Daylight Coefficient Basics
(Source: ch.6 in Mardaljevic 1999)

The total horizontal illuminance, from a hemispherical sky, produced at the measurement point, is defined as follows (see Eq. 2). The daylight coefficient approach considers both the direct and reflected light from each sky patch.

$$E = \int_0^{2\pi} \int_0^{\pi/2} D_{\gamma\alpha} L_{\gamma\alpha} \cos \gamma d\gamma d\alpha \quad \text{Eq. 2}$$

For the annual daylight simulation, a set of daylight coefficients for each analysis point is calculated, and the interior daylight levels are computed by summing the product of all daylight coefficients and sky luminance values.

3. METHODOLOGY

The simulation results of the proposed annual daylight simulation methods have been compared for three space conditions with respect to the results of complete year-runs with RADIANCE (Ward and Shakespeare 1998).

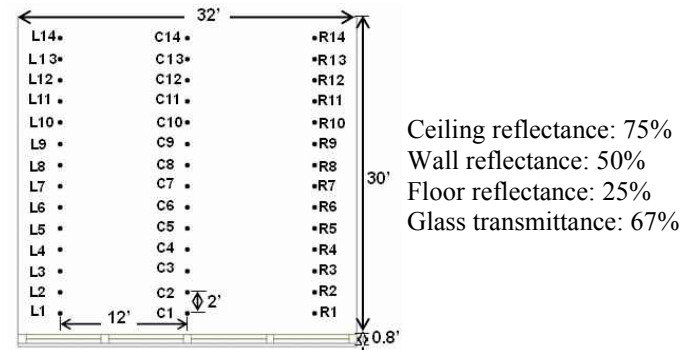
3.1 Simulation Space

Simulations have been carried out for a classroom located in Boulder, Colorado with latitude of 40 ° and longitude of 105.2 °. The test case space condition is shown in Figure 2. A single-floor, single-zone space with a floor area of 89.2 m² measuring 9.8 m wide by 9.1 m deep (960 ft², 32 ft by 30 ft) was modelled. The reflectances of the interior ceiling, wall, and floor were 75%, 55%, and 30% respectively. The floor to ceiling height was 3.7 m (12 ft). The south façade of the building includes double-pane clear windows separated by mullions into upper and lower windows. In order to compare the impact of shading device and exterior obstruction on the accuracy, the following three simulation cases were tested.

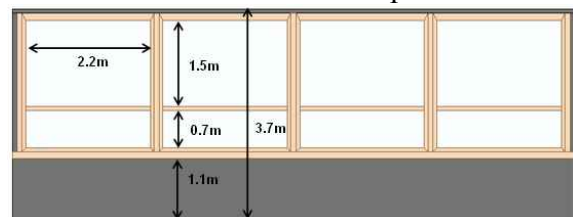
Case 1: South-facing bare window

Case 2: South-facing bare window with front obstruction

Case 3: South-facing window equipped with 30° tilted horizontal blinds



(a) Floor plan and illuminance measurement points



(b) Elevation of the south-facing front façade



(c) the exterior obstruction located in front of the space

Figure 2: Analysis Space and Illuminance Calculation Points

3.2 Weather File

The luminance distribution of each sky condition was described using the Perez all-weather model (Perez et al. 1993), generated via RADIANCE *gendaylit* program. The *gendaylit* program takes hourly direct horizontal irradiance and total irradiance input from TMY 2 weather file.

3.3 Simulation

3.3.1 Reference Simulation Approach: RADIANCE *rtrace*

As the reference simulation method to which other methods have been compared, a

series of RADIANCE *rtrace* runs were performed for every hour of sky conditions occurring throughout the year.

(a) For simulation case with window only and with front obstruction

rtrace -ab 7 -ad 2048 -as 64 -ar 32 -aa 0.1 -dt 0 -ds 0

(b) For simulation case including interior blinds

rtrace -ab 7 -ad 20000 -as 0 -ar 0 -aa 0 -lw 0.0000001

3.3.2 Daylight Coefficient Approach for the Sky

Daylight coefficients are computed with the *rtcontrib* program using the following parameters:

rtcontrib -ab 10 -ad 204800 -lw 0.000001 -as 0 -ar 0 -aa 0

Luminance of 145 Tregenza sky patches are estimated using the following parameters:

rtrace -ov -ab 0 -ad 1

4. PROPOSED ANNUAL DAYLIGHT SIMULATION METHODS

4.1 Daylight Coefficient Method for the Sky

To predict illuminance contribution from the sky, a daylight coefficient approach and the *rtcontrib* program recently implemented into RADIANCE were applied. The daylight coefficient approach divides the hemispheric sky into 145 sky patches, as shown in Figure 3, and computes the illuminance contribution from each sky patch to an illuminance measurement point including interreflections. Once daylight coefficients are computed, the illuminance contribution from the sky with an arbitrary luminance distribution can be easily calculated by multiplying the luminance values of the 145 sky patches with their respective daylight coefficients and summing the result.

4.2 Daylight Coefficient Method for the Sun

In order to achieve higher accuracy in the illuminance prediction from the sun without increasing computation time, the contribution from the sun is divided into direct and reflected components. The direct

component is calculated using *rtrace*, which takes only a few minutes for all hourly sun conditions occurring for an entire year. The reflected component 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. Therefore, this part of the procedure does not require additional calculation time. Combining the direct solar illuminance with reflected solar illuminance derived from the sky daylight coefficients (computed using *rtcontrib*) can effectively reduce the computation time for an annual daylight simulation (see Figure 4).

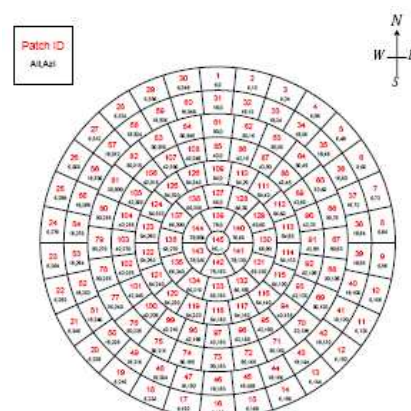


Figure 3. Tregenza Sky Patches (Source: Mardaljevic 2000, Figure 8-5)

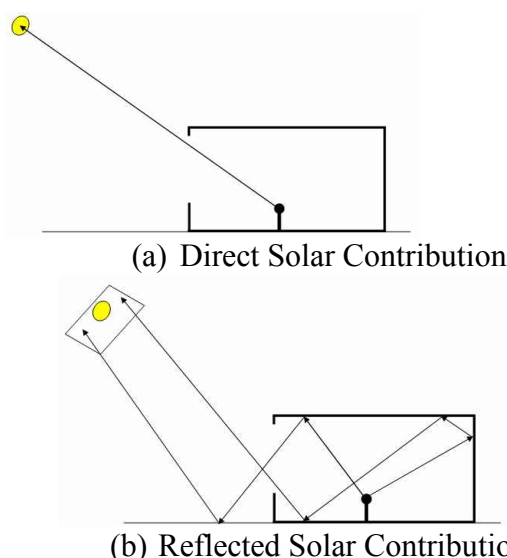


Figure 4. Daylight Coefficient Approach to compute illuminance contribution from the sun

In order to compute the reflected sun illuminance for a specific sun position, the reflected components of daylight coefficients for the four neighboring sky patches are interpolated according to relative distance between the four sky patches and the actual sun. Due to the angular size difference between the sun and a sky patch, a factor 1/724 is applied to the sun luminance.

5. SIMULATION RESULT

The internal illuminance predictions at six calculation points (C1, C7, C14, R1, R7, and R14 in Figure 2) for the annually occurring sun conditions are presented in a set of six scatter plots of the computed illuminance using RADIANCE versus matched illuminances for each simulation case.

5.1 Test of Daylight Coefficient Method for the Sky

Figure 5 illustrates the scatter plot comparing illuminances computed using the daylight coefficient approach with those computed using RADIANCE for simulation case 1. The plots show that the majority of the predictions are very accurate since the points are tightly aligned with the equality line. As shown in Figure 6 with an exterior obstruction located in front of the window, illuminance predictions at points deep within the space were underestimated, shown by negative MBEs. With interior blinds, illuminances at points near the window are underestimated, and illuminances at the back of the room are overestimated while illuminances in the middle of the space are well predicted (see Figure 7)

5.2 Test of Annual Daylight Coefficient Method for the Sun

The “Four sky patches” method provides tightly distributed data points along the equality line for simulation case 1. There is overestimation of illuminance with the “Four sky patches” mode for R14, shown by points below the equality line in Figure 8. The “Four sky patches” mode provides

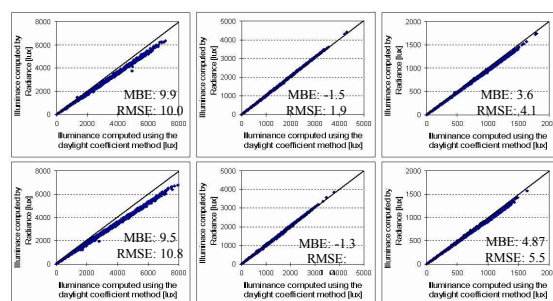


Figure 5. Comparison of the Daylight Coefficient approach and RADIANCE in the calculation of sky illuminance for simulation case 1 (south-facing window)

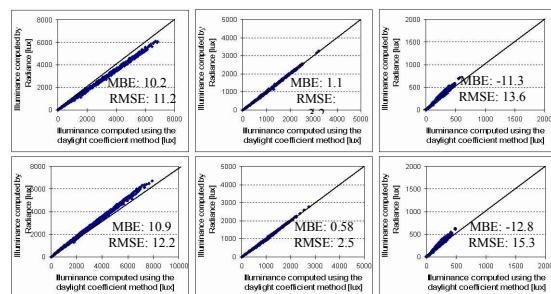


Figure 6. Comparison of the Daylight Coefficient approach and RADIANCE in the calculation of sky illuminance for simulation case 2 (south-facing window, front exterior obstruction)

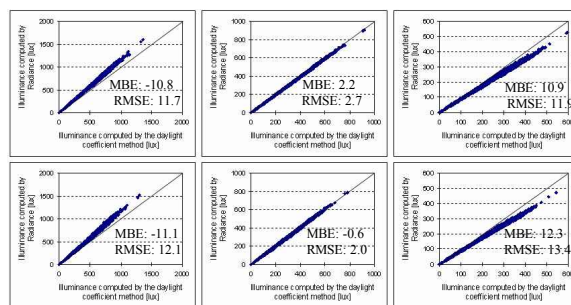


Figure 7. Comparison of the Daylight Coefficient approach and RADIANCE in the calculation of sky illuminance for simulation case 7 (south-facing, interior blinds tilted 30°)

higher illuminances than the actual sun Figure 6 because it blends the images from the sky patches located behind the exterior obstruction with the images from the sky patches above the obstruction (refer to

Figure 9). For simulation case 3, the majority of the data points are scattered around the equality line as shown in Figure 10. The daylight coefficient approach tends to overpredict illuminance at point R14. Overall, combining the illuminance contributions from the four sky patches tends to yield an overestimation of illuminance.

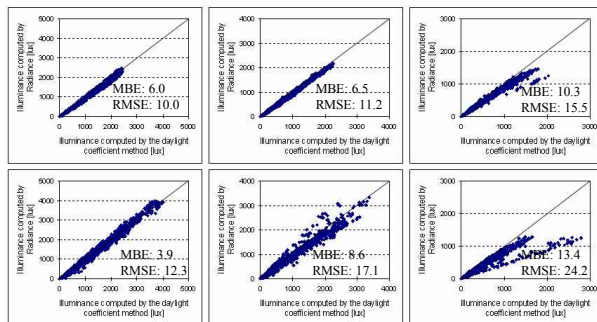


Figure 8: Comparison of the reflected sun illuminance for simulation case 1

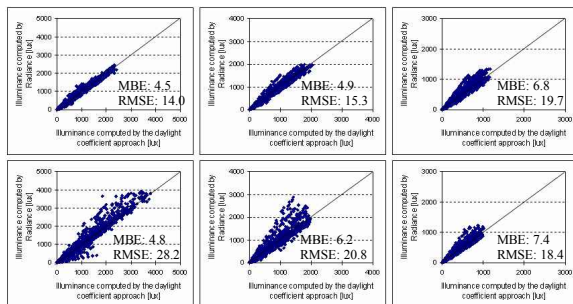


Figure 9: Comparison of the reflected sun illuminance for simulation case 2

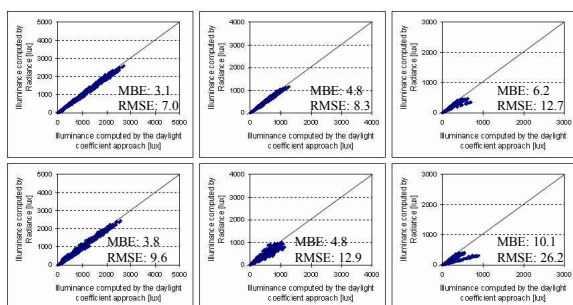


Figure 10: Comparison of the reflected sun illuminance for simulation case 3

6. CONCLUSIONS

The annual daylight simulation method based on daylight coefficients computed using *rtcontrib* in RADIANCE provides

good accuracy in the prediction of the illuminance contribution from the sky and the sun. Table 1 explains the details of this simulation method, required RADIANCE simulation parameter settings, and estimated computation time for each light source. Simulation conditions encompassing interior blinds coupled with an exterior obstruction apply the same parameter settings as simple simulation conditions.

Table 1: Summary of the proposed annual daylight simulation method for illuminance sensor modeling (100 TU = 49384.5 minutes)

	Sky	Sun	
	Total (direct + reflected) illuminance	Direct illuminance	Reflected illuminance
Method (program)	Daylight Coefficient (<i>rtrcontrib</i>)	Standard RADIANCE (<i>rtrace</i>)	Daylight Coefficient (<i>rtcontrib</i>)
Parameter settings	<i>rtcontrib</i> -ab 10 -ad 204800 -lw 0.0000001	<i>rtrace</i> -ab 0 -ad 2048 -as 64 -ar 64	
Time	0.051 TU	0.014 TU	0.002 TU

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