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Validation of Computational Algorithms for Prediction of Indoor Daylight Illuminance under Sun and Sky Conditions

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Abstract : This study proposes computational algorithms for prediction of daylight illuminance under various daylight conditions. Five annual daylight simulation methods (ADSM) were developed for the sun and sky. Computer simulations using the ADSM were performed for a classroom with an exterior overhang. In order to validate the simulation results, the results from ADSM were compared with those by Radiance. Results indicate that the prediction by a sunmatching method and reflected daylight coefficient approach were similar to those by Radiance, when methods that consider the effect of sun were used. For the methods that consider the effect of sky, the daylight coefficient approach with four sky patches provided reliable results. The result implies that daylight coefficient approach is a useful method for the prediction of daylight illuminance under daylight conditions. Linear regression models between the results of ADSM and Radiance were acceptable with a significance level of 0.01. This implies that the ADSM can be effectively used for the prediction of indoor daylight illuminance.

Key words : Computational algorithm, Daylight, Annual daylight simulation method, Radiance, Sunmatching, Daylight coefficient approach, Sky patch

1. Introduction

The energy-related issues of buildings becomes important, since the management targets for greenhouse gases and energy are supposed to be applied to buildings in 2016 (Ministry of Environment 2015). In order to design energy-efficient buildings, simulations for energy consumption are performed from the design stages to detailed development stages considering local annual weather data to predict thermal and lighting loads of buildings.

Building envelope is one of major factors that impact the building energy consumption, since solar irradiance and daylight penetrate into the interior space through the envelope. To control the amount of solar irradiance and daylight incoming, the shading devices such as overhangs or louvers are commonly installed outside of buildings. These devices impact cooling loads, heating loads and utilization of daylight. It is known that accurate predictions for interior illumiance due to daylight improve the accuracy in the estimation of building energy loads (Janak, 1997; Yoon et al., 2006).

To predict the influence of shading device on daylight availability, the geometry of shading devices should be modelled as exactly as the actual conditions of real shading devices. However, close representation of complex shading devices, such as blinds and louvers require long computation time. Thus, fixed values for visible light transmittances and shading coefficients of shading devices are commonly used in the daylighting as well as energy simulation tools. (Reinhart, 2005). This simplified procedures do not consider the variations in the transmittances and shading coefficients depending on the incoming angles of the sun and sky according to time and season.

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Therefore, annual daylight simulation method (ADSM) for spaces with shading devices that predicts the variation of daylight illuminance was developed in this study. In oder to validate the prediction accuracy of ADSM, the predicted daylight illuminance levels by ADSM were compared with those of Radiance, which was known as an effective prediction tool for illuminance under actual weather conditions.

2. Research Method

2.1. Simulation algorithms

The annual daylight simulation methods (ADSM), which were developed in this study assume that the sun and sky are separate and function as an individual light source. Based on that, two methods for the sun and three methods for the sky were developed in this study. The ADSM for the sun is classified into a sun-matching method and a reflected daylight coefficient approach (DCA). The ADSM for the sky is classified into a sky-matching method, a daylight coefficient approach with one sky patch (DCA-1) and a daylight coefficient approach with four sky patches (DCA-4).

2.2. Computation algorithms for sun

2.2.1 Sun-matching method

In the sun-matching method, the illuminance contribution from the sun is modeled using 55 representative sun positions, which are the sun positions from 8 AM to 6 PM for February 21, March 21, April 21, June 21 and December 21. These representative suns cover the full range of possible sun positions that occur throughout the year form 8 AM to 6 PM. The representative sun positions that were used for the sun-matching method are shown in Figure 1.

The actual sun is interpolated from the neighboring two suns with the same solar time, but different days encompassing lower and higher solar altitude angles. Detailed theoretical background for the sun-matching methods is explained in a previous study (Yoon, Moon, & Kim, 2015)

2.2.2 Reflected daylight coefficient approach

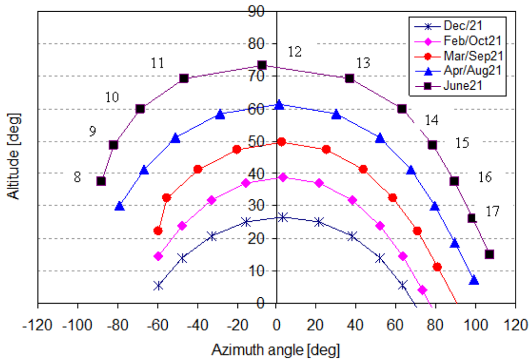

Figure 1. Representative sun positions for Boulder, Colorado, USA (Yoon, Moon & Kim, 2015).

The influences of direct and reflected component are separately considered in the illuminance calculation for the sun using the reflected daylight coefficient method. Direct daylight illuminance is calculated by the *rtrace* program of Radiance, and the reflected illuminance is calculated using the reflected components of daylight coefficients from the 145 sky patches. Daylight coefficient is defined as a ratio between the luminance of the individual sky patch and the resulting illuminance levels (Tregenza & Waters, 1983).

Combining the direct solar iluminance with the reflected solar illuminance can effectively reduce the computation time for an annual daylight simulation. The procedure of the daylight coefficient approach is as follows.

First, the reflected components of daylight coefficients for the sky are computed by subtracting the direct components from the total components of daylight coefficients according to 145 sky patches. Second, the hourly direct solar illuminance is computed using *rtrace*.

Third, the reflected solar illuminance for a given solar position is computed using the reflected components of daylight coefficients for a single sky patch containing the sun or the neighboring four sky patches. Finally, the daylight coefficients of the sky patch are reduced by the ratio of solid angle for sun in order to apply the contribution of sun to a sky patch (Mardaljevic 1999). Detailed theoretical background for the reflected daylight coefficient approach is explained in a previous study (Yoon, Moon, & Kim, 2015)

2.3. Computation algorithm for sky

2.3.1 Sky-matching method

To determine a set of representative sky types for the sky matching method, the vertical to horizontal illuminance ratio (VH ratio) on a glazing was used. Additionally, a solar azimuth angle was considered to account for the circumsolar effect.

From the hourly solar azimuth angles, the minimum and maximum solar azimuth angles were determined and the range of the solar azimuth angle was also determined. For instance, azimuth angle is divided into eight zones with a angle of 16.42°, when the azimuth angle varies from −89.96° to +107.13° in a year. The size of a single azimuth angle zone is computed by dividing the difference between the maximum and the minimum solar azimuth angles with the number of azimuth angle zones. Then, skies were grouped according to solar azimuth angle zones.

For the skies within a specific azimuth angle zone, minimum and maximum VH ratios as well as VH ratios that increase in equal steps from the minimum to the maximum were found. The increment steps were determined by the number of skies per azimuth angle zone. The skies that belong to the same solar azimuth angle zone and have the closest VH ratios to the selected VH ratios were the representative skies for the given azimuth angle zones. This selection of representative skies was repeated for other azimuth angle zones.

The simulations for the representative skies were performed. For each hour, the representative sky which has the closest VH ratio to the actual sky was used to compute the workplane illuminance for the actual sky. Also, a scaling factor was applied to account for the difference in the incident exterior vertical glazing illuminance between the actual sky and representative sky. The scaling factor is the ratio of vertical illuminance for the representative sky to that for the actual sky.

In this study, a total of 144 representative skies composed of twelve azimuth zones and twelve skies per azimuth zone were used. Detailed theoretical background for the sky-matching method is explained in a previous study (Yoon, Moon, & Kim, 2015)

2.3.2 Daylight coefficient approach

Daylight coefficient is a ratio of the luminance of a sky patch to the resulting illuminance at a point. The illuminance at the point is obtained by summing up the daylight coefficients for all sky patches that cover the entire hemispherical sky. The computation process is explained as follows.

First, the daylight coefficients for 145 sky patches for the uniformly luminous sky are computed. Second, the luminous ratios for individuals sky patches of the actual sky to the uniform sky are multiplied by the daylight coefficients.

In this study, the daylight coefficient was computed using *rtcontrib* program of Radiance. Detailed theoretical background for the daylight coefficient approach is explained in a previous study (Yoon, Moon, & Kim, 2015)

2.4. Simulation conditions

Daylight illuminances computed from the annual daylight simulation method (ADSM) under various conditions were compared with those from Radiance to validate the computation accuracy of ADSM. Radiance is a validated software to predict daylight illuminance under various daylight conditions (Reinhart et al. 2001, Maldaljevic 2000).

The space used for simulations was a classroom which was located in Boulder, CO, USA (Latitude: 40°'N, Longitude: 105°2'E). The dimensions of space were 9.6 m (width), 9.0 m (depth), and 3.7 m (height). The window was assumed to face south. The detailed layout of the space is shown in Figure 2. An overhang that consists of nine(9) louver slats was installed at the top of window to control daylight. The depth of overhang was 1.2 m and the distance between each lover slat was 13.3 cm. The width of each louver slat was 13.3 cm. The tilt angle of louver slat was 54.3°.

The reflectances of ceiling, wall, and floor were 75%, 55%, and 30% respectively. The transmittance of window for light was 67%. The ground reflectance was assumed to be 20% and no neighboring building was considered. Calculation points of horizontal illuminance were 2.4 m and 4.2 m away from the window along the center line of space. The height of calculation points was 0.75 m. Lighting fixtures were not operated. Detailed conditions used for simulations in this study are summarized in Table 1.

Sky conditions was modelled using the Perez model which was based on TMY2 weather data. The model was known to provide reliable results and used in various studies (Marion & Urvan, 1995; Perez, Seals, & Michalsky; 1993). Simulations were performed from 08:00 to 18:00 on an hourly base for an entire year. Among the simulated data, three particular days were selected for analysis in this study.

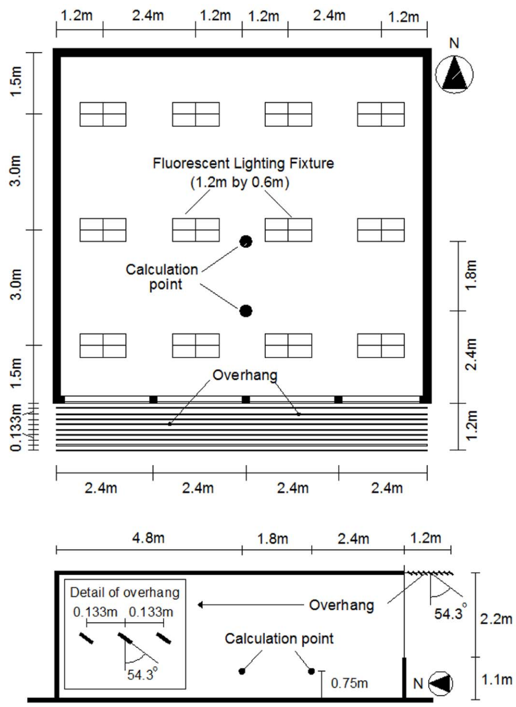

Figure 2. Layout of space (Top: Plan, Bottom: Section).

Table 1. Simulation Conditions

Orientation	South-facing
Shading device	Overhang
Day	June/21. Sep/21, Dec/21
Time	08:00-18:00 (hourly base)

3. Results

3.1. Daylight illuminance by sun

In this study, three particular days that represent specific conditions of sun positions were selected for analysis. The computed results by the sun-matching method and the daylight coefficient approach with one and four sky patches are compared with those from Radiance.

The variations of daylight illuminance for the selected three days are shown in Figure 3~8. Direct components of daylight at the two calculation points on September 21st and June 21st were blocked, since the overhang was designed to block the direct component from March to September. However, the direct component in December reached the point, which was 2.4 m away from the window.

The illuminances by the sun-matching method in

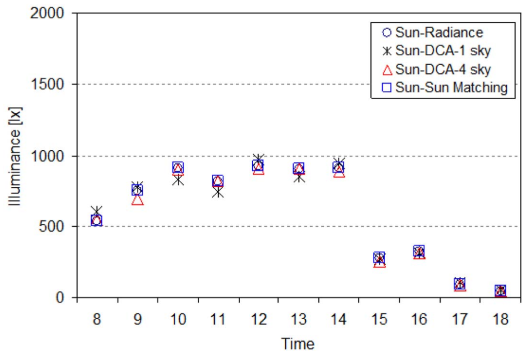

Figure 3. Difference between illuminance by Radiance and ADSM (June/21, 2.4 m).

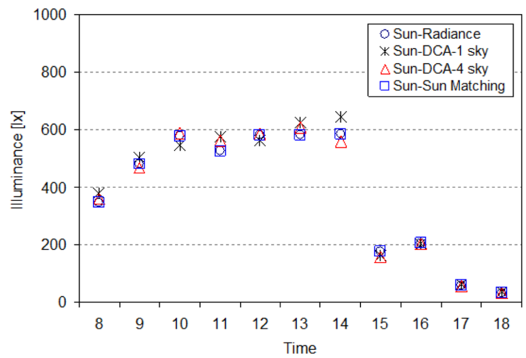

Figure 4. Difference between illuminance by Radiance and ADSM (June/21, 4.2 m).

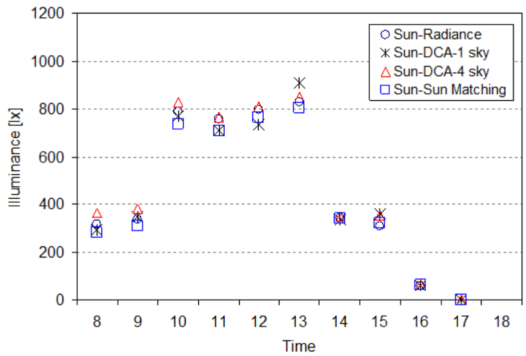

Figure 5. Difference between illuminance by Radiance and ADSM (Sep/21, 2.4 m).

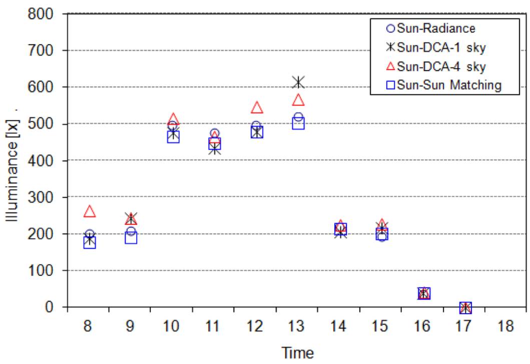

Figure 6. Difference between illuminance by Radiance and ADSM (Sep/21, 4.2 m).

June and December was similar to those by Radiance. For instance, the maximum illuminance difference between them was 47 lx in September. It appears that insignificant difference existed between the results, since the direct component was blocked by the overhang and only the reflected component was available in space.

The illuminance levels by the daylight coefficient approach with one sky and four sky patches were similar to those by Radiance. For instance, at the point which is 4.2 m away from window, illuminance difference between Radiance and the daylight coefficient with one sky patch was 18% (95 lx). When the daylight coefficient approach with four sky patches was used the illuminance difference between them was 9% (48 lx).

As shown in Table 2, the results by the sun-matching method showed similar results to the results from Radiance compared with the other methods. The results from the daylight coefficient approach deviated further compared to the sun-matching method. In particular, the method with one sky patch enerated lower illuminances compared to the method with four sky patches.

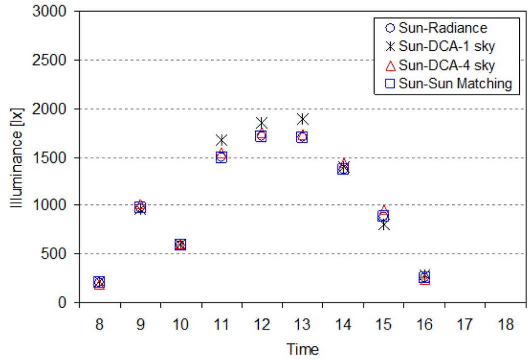

Figure 7. Difference between illuminance by Radiance and ADSM (Dec/21, 2.4 m).

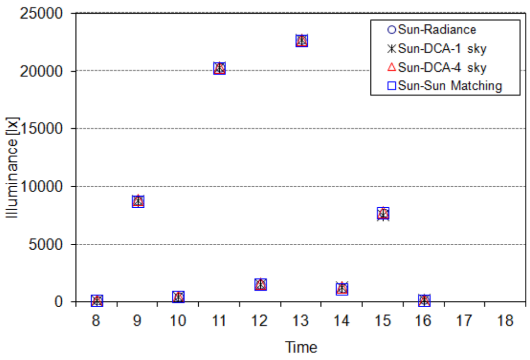

Figure 8. Difference between illuminance by Radiance and ADSM (Dec/21, 4.2 m).

Table 2. Statistics for Difference between Radiance and ADSM (Radiance - ADSM)

Statistics	Sun match	DCA (1 sky)	DCA (4 sky)
Mean	4.86	−13.96	−23.86
Mode	0.00	−13.40	−10.10
Std. Deviation	11.53	59.75	45.66
Range	61.00	419.40	317.40
Min.	−9.80	−242.90	−257.50
Max.	51.20	176.50	59.90

The Pearson correlation between the results from the three methods of ADSM and Radiance was summarized in Table 3. Overall, the Pearson coefficients were greater than 0.999. The daylight coefficient

Table 3. Pearson Correlation between Illuminance by Radiance and ADSM

Method	Statstics	Radiance	Sunmatching	DCA (1 sky)	DCA (4 sky)
Radiance	P.C	1.00			
	Sig.				
	N	87			
Sunmatching	P.C	0.9996	1.00		
	Sig.	0.00			
	N	83	83		
DCA (1 sky patch)	P.C	0.9998	0.9919	1.00	
	Sig.	0.00	0.00		
	N	87	83	87	
DCA (4 sky patch)	P.C	0.9999	0.9947	0.9998	1.00
	Sig.	0.00	0.00	0.00	
	N	87	83	87	87

where, - P.C.: Pearson Correlation

approach with four sky patches showed the strongest correlation with Radiance. This result implies that the ADSM developed in this study effectively predict the effect of sun.

3.2. Daylight illuminance for sky

The computation results by the daylight coefficient approach and the sky-matching method are compared with the results of Radiance. The comparisons are shown in Figure 9~14. The results by the daylight coefficient approach were closer to those by Radiance. In particular, the illuminance levels by the sky-matching method in September were greater than those in June and December.

The shading devices installed at the top of window prevents the view from the calculation point to the sky. Hence, direct components in the real sky and the representative sky were different. For instance, the sky at 11 a.m was matched with the representative sky at 11 a.m on May 18.

Vertical to horizontal illuminace ratio between the two skies was 2.04. Solar altitude at 11 a.m on September 21 and May 18 were 45.15° and 61.8°, respectively. The difference in the azimuth angle between the two conditions was 18°. Hence, the luminous pattern to indoor space due to the sky differs from that

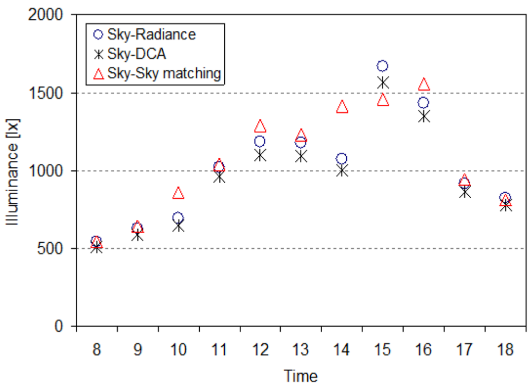

Figure 9. Difference between illuminance by Radiance and ADSM (June/21, 2.4 m).

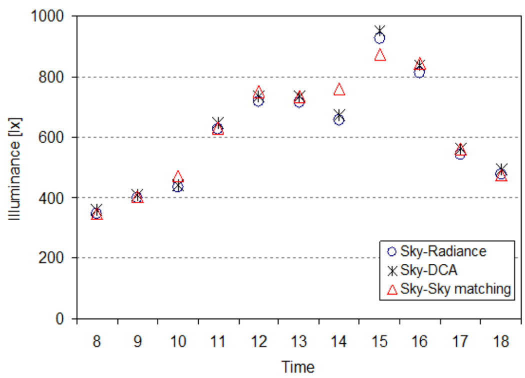

Figure 10. Difference between illuminance by Radiance and ADSM (June/21, 4.2 m).

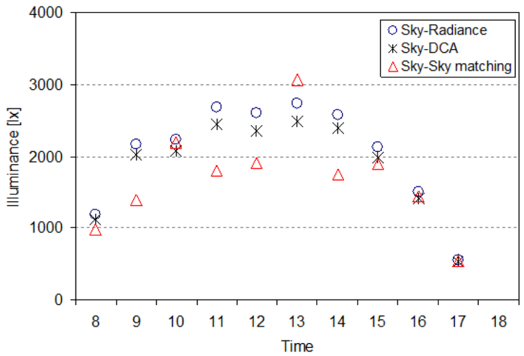

Figure 11. Difference between illuminance by Radiance and ADSM (Sep/21, 2.4 m).

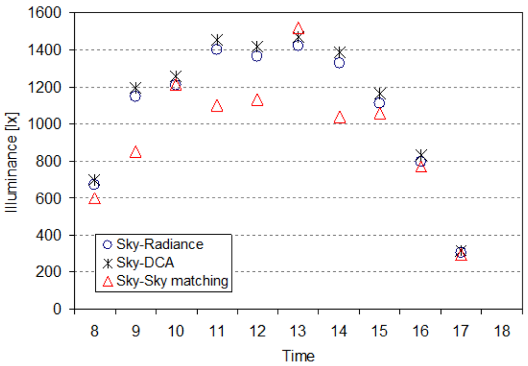

Figure 12. Difference between illuminance by Radiance and ADSM (Sep/21, 4.2 m).

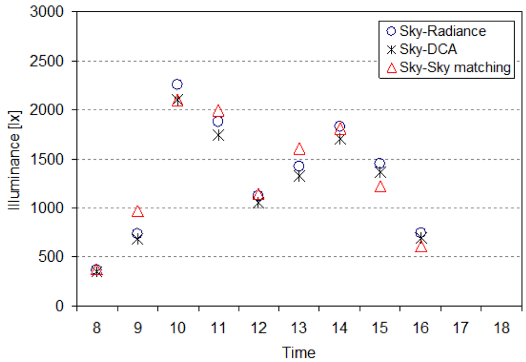

Figure 13. Difference between illuminance by Radiance and ADSM (Dec/21, 2.4 m).

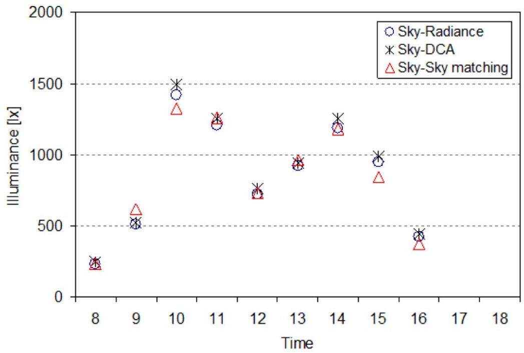

Figure 14 Difference between illuminance by Radiance and ADSM (Dec/21, 4.2 m).

Table 4. Statistics for Difference between Radiance and ADSM (Radiance - ADSM)

Statistics	Sky-matching	Sky-DCA
Mean	47.89	21.85
Mode	–11.90	–10.80
Std. Deviation	196.37	69.39
Range	1224.80	329.60
Min.	–337.70	-75.60
Max.	887.10	254.00

of the representative sky at 11 a.m on September 21. This results in different indoor illuminance levels.

As shown in Table 4, illuminance levels by the sky-matching method and the daylight coefficient method were lower than those by Radiance. For instance, the difference between the sky-matching method was approximately twice as great as the illuminance difference between the daylight coefficient approach and Radiance.

Table 5. Pearson Correlation between Illuminance by Radiance and ADSM

Method	Statistics	Radiance	Sky matching	DCA
Radiance	P.C	1.00		
	Sig.			
	N	90		
sky matching	P.C	0.9495	1.00	
	Sig.	0.00		
	N	90	90	
DCA	P.C	0.9965	0.9456	1.00
	Sig.	0.00	0.00	
	N	90	90	90

where, - P.C.: Pearson Correlation

The Pearson correlations between Radiance and computation results by the two methods of ADSM for the sky are summarized in Table 5. The Pearson

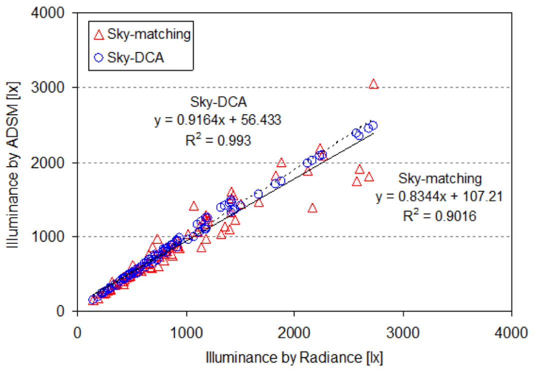

Figure 15. Relationship between illuminance by Radiance and ADSM for sky.

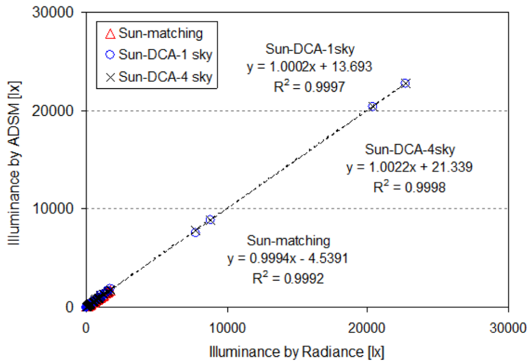

Figure 16. Relationship between illuminance by Radiance and ADSM for sun.

coefficient between the sky-matching method and Radiance was 0.9495. The coefficient between the daylight coefficient approach and Radiance was 0.9965. This result implies that the computation results by daylight coefficient approach was closer to those by Radiance.

3.3. Correlation analysis

Linear regression analysis was used to analyze the correlation between the computation results from the annual daylight simulation method (ADSM) and Radiance. The results from Radiance was used as independent variables and the results from the ADSM was used as dependent variables in regression models. ANalysis Of VAriable (ANOVA) was used to test the models.

Detailed regression results are shown in Figure 15 and 16. Overall, the results from the ADSM and Radiance were strongly correlated with each other. When the contribution of sky was considered, the coefficients of determination (r^2) that imply the correlation between them were 0.9016 and 0.9930. Compared to the sky-matching method, the daylight coefficient approach generated prediction results which are closer to those by Radiance.

When the effect of the sun was considered, the coefficient of determination was greater than 0.99. This implies that the ADSM developed for the sun can predict illuminance more accurately compared to the ADSM for the sky. These results appear to occur since direct components from the sun was blocked by overhangs, and reflected components were available in space.

The ANOVA test results for the regression models are summarized in Table 6~10. Overall, all models were acceptable with a significance level of 0.01.

Table 6. ANOVA for Relationship between Radiance and Sky-matching of ADSM

Variable	Unstandardized Coefficient		t	Sig.
	B	Std. Error		
(Constant)	0.834	0.029	3.27	0.00
Radiance-Sky	107.21	32.81	28.39	0.00
ANOVA	$F(1,88) = 806.14$, Sig. = 0.00, $R^2 = 0.9016$			

Table 7. ANOVA for Relationship between Radiance and Daylight Coefficient Approach of ADSM

Variable	Unstandardized Coefficient		t	Sig.
	B	Std. Error		
(Constant)	56.43	9.160	6.16	0.00
Radiance-Sky	0.916	0.008	111.67	0.00
ANOVA	$F(1,88) = 12469.49$, Sig. = 0.00, $R^2 = 0.9930$			

Table 8. ANOVA for Relationship between Radiance and Sun-matching Method of ADSM

Variable	Unstandardized Coefficient		t	Sig.
	B	Std. Error		
(Constant)	-4.539	1.999	-2.27	0.03
Radiance-Sun	0.999	0.003	323.59	0.00
ANOVA	$F(1,81) = 104709.52$, Sig. = 0.00, $R^2 = 0.9992$			

Table 9. ANOVA for Relationship between Radiance and Daylight Coefficient Approach with 1 Sky Patch of ADSM

Variable	Unstandardized Coefficient		t	Sig.
	B	Std. Error		
(Constant)	13.693	6.815	2.01	0.05
Radiance-Sun	1.000	0.002	522.21	0.00
ANOVA	$F(1,85)$= 272705.76, Sig. = 0.00, R^2 =0.9997			

Table 10. ANOVA for Relationship between Radiance and Daylight Coefficient Approach with 4 Sky Patches of ADSM

Variable	Unstandardized Coefficient		t	Sig.
	B	Std. Error		
(Constant)	21.339	5.142	4.15	0.00
Radiance-Sun	1.002	0.001	693.50	0.00
ANOVA	$F(1,85)$ = 480943.08, Sig. = 0.00, R^2 = 0.9998			

This result means that the models can be used to determine the correlation between the prediction results by ADSM and Radiance.

4. Conclusion

Computation algorithms were developed in this study in order to predict daylight illuminance values under various conditions for the sun and sky. Simulations were performed for a space with exterior overhangs. The simulation results were compared with those of Radiance. A summary of findings is as follows.

1. Among the computational algorithms that considers the influence of sun, the sun-matching method and reflected daylight coefficient approach generated prediction results close to those from Radiance. This can be explained that the direct component of sun was effectively blocked by the overhangs and not allowed to penetrate into the indoor space. The prediction results from the reflected daylight coefficient approach using four sky patches were closer to those from Radiance, compared to the method using one sky patch.

2. Among the computation algorithms for the sky, the illuminance levels predicted by the daylight coefficient approach was closer to those predicted by Radiance, compared to the sky-matching method. These results imply that predictions by the daylight coefficient method are reliable for the prediction of annual daylight availability.

3. Linear regression models that explain the relationship between Radiance and five computation algorithms of ADSM were valid with a significance level of 0.01. This means that the ADSM can be applied to determine the illuminances due to the sun and sky for a space with shading devices instead of individual Radiance runs.

In this study, the simulation were conducted under limited conditions and the results were compared with the results by a particular software. The results of this study confined to a comparison for simulation results using different simulation software.

Comparing the prediction results with those from various simulation software would be helpful, since computational algorithms in the software have various strength and weakness in computation. Also, the prediction results discussed in this study should be compared with those from field measurements under actual building conditions to provide strong validation.

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