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A Study of Daylight Modeling Approaches Applied in LEED

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ABSTRACT

The most recent version of the U.S. Green Building Council's LEED (v4.1) for Building Design & Construction provides three options for assessing the Daylight Credit. The first two options are based on computer simulation, whereas the third relies on physical measurement. Option 1 requires annual simulation of Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). Option 2 applies a point-in-time approach, which demonstrates through computer modeling that a sufficient area of a space will have illuminance levels between 300 lux and 3,000 lux at both 9 a.m. and 3 p.m., on a clear-sky day at the equinoxes. Option 3 involves measurements (following construction) of daylight performance on multiple days and hours, with no consideration of interior shading. According to USGBC, Option 2 has been the mostly used approach for certified projects that received a daylight credit. This research focuses on the two simulation options to assess whether their results are in general agreement, assessing whether a space which contributes to points under one option would also contribute under the other option, given that Option 1 and Option 2 apply very different approaches. To this end, an office space model, on the ground floor of building, with dimensions of 9.1m × 9.1m × 3.0m and a Window to Wall-Ratio (WWR) of 40% has been simulated under a variety of conditions for both options. Simulations were run in 6 different cities, considering a variety of window orientations and two different interior shading devices. The findings of this study clearly show that the two simulation approaches for quantifying the percentage of a space that is daylit for the purpose of evaluating LEED credits, can deliver significantly different results, with Option 2, which assess daylight at only two hours of the year for clear skies only predicting much higher daylight coverage than Option 1 for certain space and site conditions.

INTRODUCTION

Across various versions of *the U.S. Green Building Council's Leadership in Energy and Environmental Design* (LEED), the intent of the Daylight Credit, as stated in the LEED daylight credit section has been modified slightly, from "to provide for the building occupants a connection between indoor spaces and the outdoors through the introduction of daylight and views into the regularly occupied areas of the building" in LEED v2, to "to connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing adequate daylight into the building" in LEED v4.1. Additionally, the credit requirements and assessment methods have evolved over time. The last version of LEED (v4.1) provides three options for assessing the Daylight Credit and the most widely used approach is Option 2, which applies illuminance levels across the work plane in a point-in-time calculation, however, Option 1 applies the most recent daylight evaluation metrics, which consider performance across the year. USGBC documentation shows that out of 281 projects certified by LEED v4, only 42 projects attempted Option 1, while 175 projects adopted Option 2 and 64 remaining projects attempted Option 3 (E-mail interview 2020). It is worth mentioning that there are no v4.1 projects with Daylight Credit (EQ121) certified to date. Considering the Option 1 and Option 2 detailed methods for daylight evaluation, Option 2 is an easier method to apply since it does not require the user to establish window groups within each space to which shading devices are applied, nor apply advanced software that is capable of performing the hourly analysis with different shading conditions, as required for Option 1. Option simply applies clear sky conditions at two hours of the year with no blinds or shades being triggered under certain conditions on windows. Given the large

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differences in these two approaches, a logical question to ask is whether these two options deliver consistent results, which is the focus of the research effort that is reported here.

Daylight Assessment Metrics

Analyzing daylight performance of a space has evolved from static approaches towards dynamic, climate-based daylight simulations during last decades (Reinhart et al. 2006). Daylight Factor (DF), one of the widely used static approaches, was introduced in 1892 by Trotter (Walsh 1951). DF is defined as the ratio of indoor illuminance (E_{indoor}) at a point in a building to the unshaded, outdoor horizontal illuminance ($E_{outdoor}$) under an overcast sky condition (Reinhart et al. 2006). The limitation of DF is that building location, orientation, season, and time of day are excluded from the calculation. To address the limitations of DF, Climate-Based Daylight Modeling (CBDM) metrics were developed. *The Illuminating Engineering Society* (IES) introduced two new CBDM metrics, Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), in 2012. LEED v4.1 uses these two metrics in the Option 1 compliance path for the Daylight Credit. IES-LM83 describes sDA as a dynamic metric for assessing the sufficiency of ambient daylight levels in interior environments throughout the year. It is defined as the percent of an analysis area (the area where calculations are performed - typically across an entire space) that meets a 300-lux minimum daylight illuminance level for 50 percent of the operating hours per year. ASE is a metric that evaluates the potential for visual discomfort, measuring the percent of the floor area that exceeds 1000 lux of direct sunlight for more than 250 hours per year, before any operable blinds or shades are deployed to block sunlight (IES-LM83-12n). With increased computing power and faster algorithms, CBDM's, such as these, provide a more realistic assessment of daylighting performance across the year, and are now being embedded into codes and standards.

Evolvement of LEED Daylight Credit

DF was applied in the early versions of LEED (v2 2001) to qualify for the Daylight Credit, which required a 2-percent DF over 75 percent of the area where critical visual tasks would occur. LEED then moved to sky-based metrics in 2009, where 75 percent or more of the applicable spaces needed to achieve daylight illuminance minima of 10foot candles (fc) (110 lux) and a maximum of 500 fc (5,400 lux) under a clear sky condition on the September equinox at 9 a.m. and 3 p.m. Glare control devices were also to be provided, demonstrating compliance with the minimum 10 fc (110 lux) requirement (LEED v3 BD+C 2009). LEED 2009 also provided projects with *Prescriptive Calculations* and *Measurement* options.

LEED v4 went one step further and fully adopted the CBDM approach, and provided three options for evaluating Daylight Credit through computer simulation and measurement. Option 1 adopted the new IES metrics of sDA and ASE. To achieve a single point from Option 1, projects needed to demonstrate that 55 percent or more of the regularly occupied floor area achieved 300 lux for at least 50 percent (sDA) of the total occupied hours of the year, and that annual sunlight exposure of 1000 lux occurred no more than 250 hours over less than 10 percent of the occupied floor area (but the area was quickly extended to 20 percent).

Option 2 applied a point-in-time calculation and compliant projects needed to demonstrate through computer modeling that illuminance levels of 75 percent or more of the regularly occupied floor area was between 300 lux and 3,000 lux for 9 a.m. and 3 p.m. on the clearest sky day near the equinoxes found in the weather file (within +/- 15 days of September 21st and March 21st).

Option 3 required projects to show though measurement that 75 percent or more of regularly occupied floor area achieved illuminance levels between 300 and 3,000 lux through measured data during any hour between 9 a.m. and 3 p.m. in two different months, the first day could be in any regularly occupied month, with the second at least 5 months later (Table 1) (LEED v4 BD+C 2014).

Table 1. Points for LEED Options (LEED v4.1)

Option 1		Option 2		Option 3	
Percentage of regularly occupied floor area	Points	Percentage of regularly occupied floor area	Points	Percentage of regularly occupied floor area	Points
The average sDA300/50% value for the regularly occupied floor area is at least 40%	1	55%	1	55% at one time in the year	1
The average sDA300/50% value for the regularly occupied floor area is at least 40%	2	75%	2	75% at two times in the year	2
The average sDA300/50% value for the regularly occupied floor area is at least 40%	3	90%	3	90% at two times in the year	3

The most recent version of LEED (v4.1) provides almost similar options to LEED v4 but with lower entry thresholds to encourage more projects to consider daylight performance during design (LEED v4.1). In LEED v4, Option 1 provided more points than Option 2, but in LEED v4.1 all options provide up to 3 points. In LEED v4, projects had to demonstrate that 55 percent or more of the regularly occupied floor area achieved 300 lux for at least 50 percent of total occupied hours of the year to achieve 1 point under Option 1, but LEED v4.1 decreased the minimum area percentage to 40 percent and Option 2 was changed from 75 percent to 55 percent to achieve one point.

Objectives

Since the two simulation-based approaches, Options 1 and 2, used in LEED v4.1 vary significantly in their approach, this paper focuses on a study intended to assess whether the results from these options are aligned. For good agreement, if a space contributes to points in one option, it should also contribute at the same points level if the other option is applied.

RESEARCH METHODOLOGY

To consider whether Option 1 and Option 2 show aligned results, various daylight availability conditions that differ in location, orientation, and shading condition were examined.

Model Configuration

A single office space located on the ground floor of a hypothetical three-story building was selected for this study, with dimensions of 9.1 m x 9.1 m x 3.0 m (30 × 30 × 10 ft). A single wall includes a window with a Window-to-Wall Ratio (WWR) of 40 percent (Figure 1). Furniture and partitions are excluded, and the model is assessed for eight different window orientations (S/SW/SE/W/E/N/NW/NE), given that various orientations receive different levels and directions of sunlight. The 3D model is setup through Rhino, then is converted into rad files and simulated using Honeybee[+] (HB[+]). As required by LM-83, the facade was extended to account for the full height and width of the building, and an exterior ground plane was added to catch shadows. The exterior wall is 1-foot thick and the window glass is located at the interior plane of the aperture. The surface reflectances and window properties are shown in Table 1:

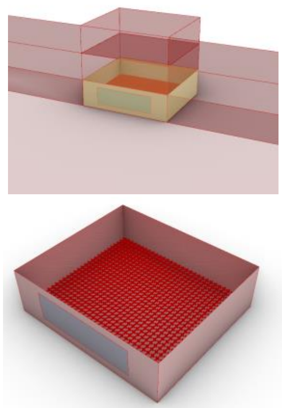

Figure 1 Test model for research

Table 2: The surface reflectances and window properties

Finished surface	Surface reflectance
Ceiling	80%
Wall	50%
Floor	20%
Ground	15%
Exterior wall	30%
Overhang	50 %
Material properties of the window	
Window element	**Optical properties**
glazing	60 % Visible Light Transmittance (VLT)
Roller shades parameters	
Diffuse VLT	5%
Specular transmittance	0%

Sites and locations

A U.S. city was selected from each of the five daylight zones in North America as defined by Reinhart (2014). These cities were selected based on sunshine conditions:

Table 3. Five cities selected for research

Location	Latitude	Annual mean total sunshine hours
Phoenix, AZ	33.43˚	>3400
Miami, FL	25.76˚	3000-3200
Bismarck, ND	46.80˚	2601-2800
Seattle, WA	47.45˚	2200-2400
Pittsburgh, PA	40.50˚	2000-2200

Simulation Method and Parameters

Option 1 and Option2 were simulated in HB[+] for the five cities for the eight different window orientations. Based on LEED *Reference Guide for Building Design and Construction* (2014) TMY weather data of the nearest station was used. The simulation results compare Option 1 and Option 2 in terms of the percentage of daylit area that contribute toward attainment of LEED daylight credits and the LEED points that are associated with this coverage level.

Option 1

Option 1 is based on sDA simulations. To calculate sDA in HB[+],windows must be modeled with interior shading and whenever more than 2 percent of the analysis points receive direct sunlight, the shading devices are to be lowered. In this model, a fabric roller shade was a surface with translucent material that covered the entire window and was installed just inside the window glass. This roller shade is modeled with 5 percent diffuse VLT and no specular transmittance. These values are stated by IES LM 83-12 to be used when the shade properties are unknown. Nezamdoost et al. (2018) indicates that a 2 percent shade trigger appears to produce less window occlusion than may occur in real spaces with user-controlled blinds, or through the use of automated shade control.

HB[+] doesn't consider shading in sDA calculation, so a customized Python component was written to assess the direct sunlight across the analysis grid and apply the results from a simulation with shade when more than 2 percent of grid surface received direct sunlight in computing a final sDA value. The common analysis period of 8 a.m. to 6 p.m. local time was applied across a full calendar year, and the analysis area calculation grid applied a spacing of 30 cm at a 76 cm height.

Option 2

The simulation methodology for Option 2 (point-in-time) calculated the percentage of floor area that achieved an illuminance level between 300 and 3000 lux at the same analysis points as applied in Option 1. Although LEED requests calculations at 9 a.m. and 3 p.m., the weather files only have data that is centered on the half hours, so 8:30 a.m. and 2:30 p.m. local time were selected for the Option 2 study. The simulation process was repeated four times: at 8:30 a.m. and 2:30 p.m. (for all cities except Phoenix) to account for daylight savings time for the day within 15 days of both March 21 and September 21 that had the clearest sky at these times. Simulations for Phoenix were performed at 9:30 a.m. and 3:30 p.m. because Arizona doesn't apply daylight saving time. The final value is the average of the percentage of points falling within the illuminance range across the four conditions.

Honeybee [+] Simulations

Honeybee [+] 0.0.06 is an open-source plug-in for Grasshopper. HB[+] uses Radiance-based workflows for daylighting simulations and its daylight coefficient simulation method was applied in this study (Grasshopper3d.com).

IES LM 83-12 recommends selecting high simulation parameters (ambient bounces = 6) to ensure reliable results. HB[+] has three levels of complexity for simulation, including low, medium, and high. High complexity was applied to both simulations for both options. Therefore, the Radiance parameters applied were:

ab, AMBIENT BOUNCES: 6 ad, AMBIENT DIVISIONS: 4096 ar, AMBIENT RESOLUTION:126
aa, AMIBIENT ACCURACY: 0.1 as, AMIBIENT SUPERSAMPLES: 4096

Results

As mentioned before, the purpose of this study was to examine the two simulation options of the LEED (v4.1) Daylight Credit for consistent results. The points achieved for the simulated space under Option 1 and Option 2 for the five cities and eight orientations are recorded in Table 3.

Table 4. Achieved points through Option 1 and Option 2 in five locations and eight orientations

	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
Orientation	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**
South	0	2	0	1	0	1	0	1	0	1
Southwest	0	1	0	1	0	1	0	1	0	0
West	0	1	0	1	0	0	1	1	0	1
Northwest	1	0	1	0	0	0	1	0	0	0
North	1	0	1	0	0	0	2	0	0	0
Northeast	1	0	0	0	0	0	1	1	0	0
East	0	1	0	0	0	0	0	1	0	0
Southeast	0	1	0	1	0	1	0	1	0	1

As can be seen in Figure 2, Option 1 and Option 2 results are somewhat reversed. For example, a south-facing space where more than 70 percent of the space is daylit under the conditions of Option 2, but less than 20 percent daylit based on Option 1. The same happens in other orientations except for the three north-facing spaces. Figure 2 shows that a single space with a north-facing window is more daylit than other orientations through Option 1, in contrast to Option 2 where it receives the least amount of daylight.

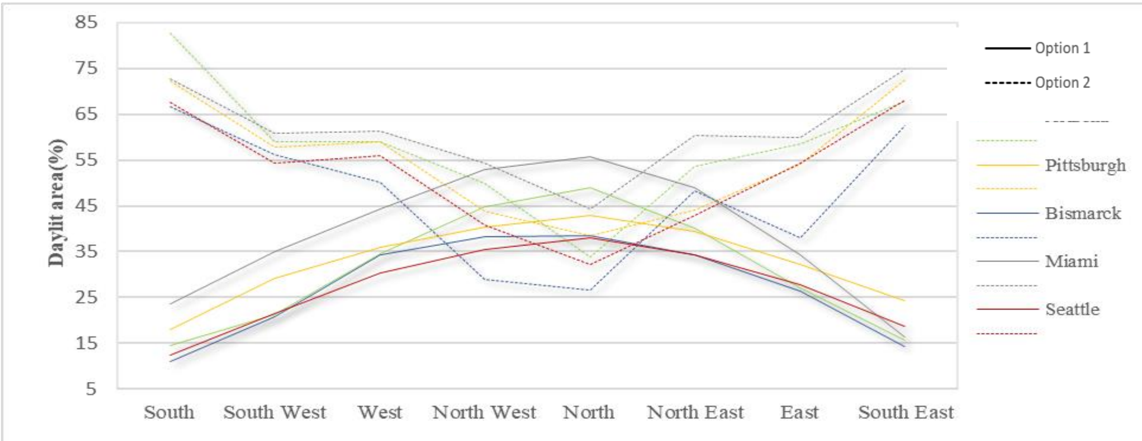

Figure 2 Option 1 vs Option 2 in terms of daylit area percentage

In the following sections, we look into the data further to consider what factors contribute to these inconsistent results. As mentioned above, for Option 1, the exterior windows must have blinds or shades applied whenever more than 2 percent of the analysis area receives 1000 lux or more of direct sunlight, while for Option 2, no such shading is applied. To understand how this difference contributes to the inconsistent results, the number of hours that shades are closed in Option 1 has been calculated and shown in Table 4. The total hours in the sDA study are 3650 (10 hours per day, 8AM to 6PM local time, for a full calendar year of 365 days.

Table 5. The number of hours with down-shades

	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
Orientation	**sDA(%)**	**Hours**	**sDA(%)**	**Hours**	**sDA(%)**	**Hours**	**sDA(%)**	**Hours**	**sDA(%)**	**Hours**
South	14.57	2152	18.04	1580	10.87	2119	23.65	1703	12.42	1710
Southwest	21.14	1650	29.15	1125	20.66	1395	34.88	1430	21.5	1185
West	34.52	1102	35.96	679	34.4	778	44.32	1017	30.22	696
Northwest	44.68	439	40.38	262	38.35	175	53.04	480	35.36	256
North	48.86	100	43.01	28	38.59	79	55.65	80	38.11	0
Northeast	40.02	871	39.3	428	34.28	604	48.86	831	34.4	394
East	27	1527	32.25	884	26.28	1193	34.28	1420	27.71	906
Southeast	15.65	2095	24.25	1310	14.21	1854	16.24	1795	18.75	1347

Table 4 reveals that the roller shade has a significant impact on the results of Option 1. In locations such as Phoenix, which is mostly sunny throughout the year, more than half of the total simulation hours (3650) consider interior shading. In contrast, the number of hours that shades are down is less in cloudy cities like Pittsburgh and Seattle.

Table 4 and Figure 3 also make clear why north-facing spaces are performing better in terms of daylight availability using Option 1. As can be seen in Table 4, shades are down less than 100 hours in spaces with northern windows in almost all the locations, and these have the highest sDA values. There is also a similar trend in spaces with windows facing northwest and northeast.

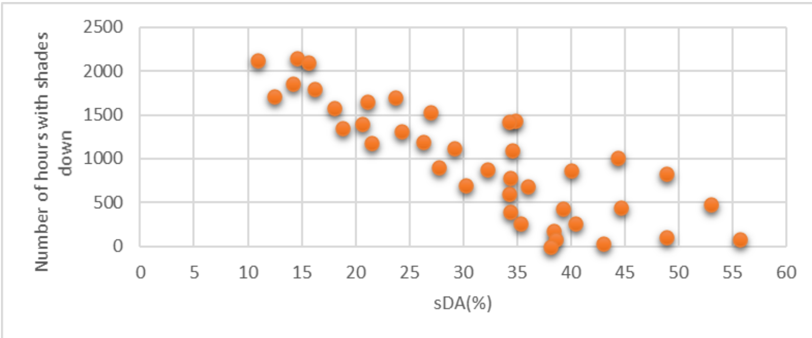

Figure 3 Relationship between sDA and the number of hours that shades are applied for a 5 percent transmittance diffuse shade (graph shows all locations and orientations from Table 3)

As a means of bringing results into better alignment, two measures for controlling daylighting in spaces, consistent with principles of sustainable design and synergies and tradeoffs considered when pursuing LEED v4.1 were simulated. These are: changing the transmittance of the interior blinds and adding an external shading overhang.

While the above utilizes the IES LM 83-12 default value of 5 percent Diffuse Transmittance (DT) with no specular transmittance (for when the roller shade properties are unknown), we also considered a higher amount of DT (20 percent) which, according to LM-83 can be applied to consider the performance of 80 percent reflective horizontal blinds. Table 5 shows that the results for this condition are better aligned with Option 2.

Table 6. Achieved point through Option 1 with a roller shade with 5 percent DT vs Option 2

	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
Orientation	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**
South	1	2	0	1	1	1	1	1	0	1
Southwest	1	1	1	1	1	1	1	1	1	0
West	1	1	1	1	1	0	1	1	0	1
Northwest	1	0	1	0	0	0	1	0	0	0
North	1	0	1	0	0	0	2	0	0	0
Northeast	1	0	1	0	0	0	1	1	0	0
East	1	1	1	0	1	0	1	1	0	0
Southeast	1	1	1	1	1	1	1	1	0	1

Table 5 shows in some cases, Option 2 still achieves more points than Option 1 (Phoenix, Pittsburgh, and Seattle for a south-facing window). In contrast, we see that in Pittsburgh and Bismarck, an east-facing space gets one point, while Option 2 provides no points.

As shown in Figure 4, increasing the shade diffuse transmittance from 5 percent to 20 percent makes a noticeable difference in the resulting sDA for sun-facing orientations. As mentioned before, the number of hours that shades are down is less in north-facing spaces, and thus changes in the shade transmittance have less impact on the results for these orientations.

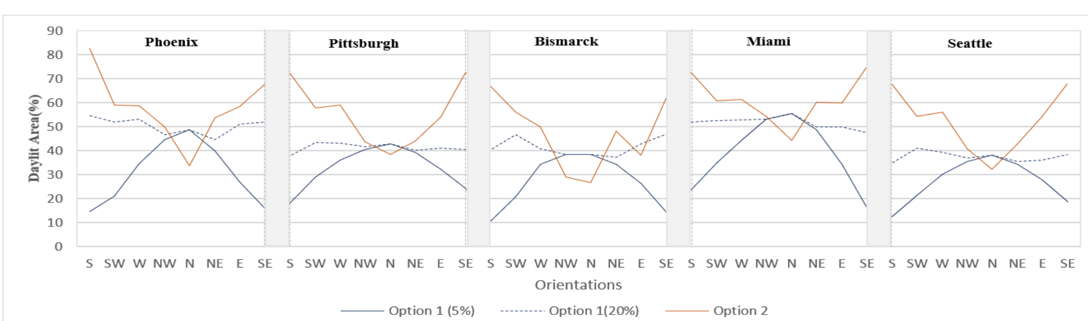

Figure 4 Option 1 vs Option 2 with both a 5 percent and 20 percent diffuse transmittance applied to Option 1

In the third and final scenario, a horizontal overhang with a 3-foot depth that is 3-foot wider than the window width was applied to the window. Table 6 shows how adding an overhang to the model affects the results of Option 1 and Option 2 in terms of achieved LEED point level and the percentage of daylit area for a 5-percent diffuse transmittance roller shade.

Table 6 shows that LEED daylight points level achieved changes when the overhang is added to the model. It is evident that locations with more sunshine hours (Phoenix, Miami) achieved points under Option 1 are increased in South and Southwest orientations. Adding an overhang leads to fewer hours with closed shades, and as a result, more daylight penetrates into the space. Results for Option 2 show an opposite trend after adding the overhang. As can be seen in Table 6, points are reduced in some orientations. Figure 5 shows graphically how the Option 1 data impacted different directions, while the Option 2 results always decreased with the addition of an overhang.

Table 7. Achieved points through Option 1 and Option 2 after adding an overhang

	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
Orientation	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**
South	1	1	0	1	0	1	1	1	0	1
Southwest	1	1	0	1	0	0	1	1	0	0
West	0	0	0	0	0	0	1	0	0	0
Northwest	0	0	0	0	0	0	1	0	0	0
North	0	0	0	0	0	0	1	0	0	0
Northeast	0	0	0	0	0	0	0	0	0	0
East	0	1	0	0	0	0	0	1	0	0
Southeast	0	1	0	1	0	1	0	1	0	1

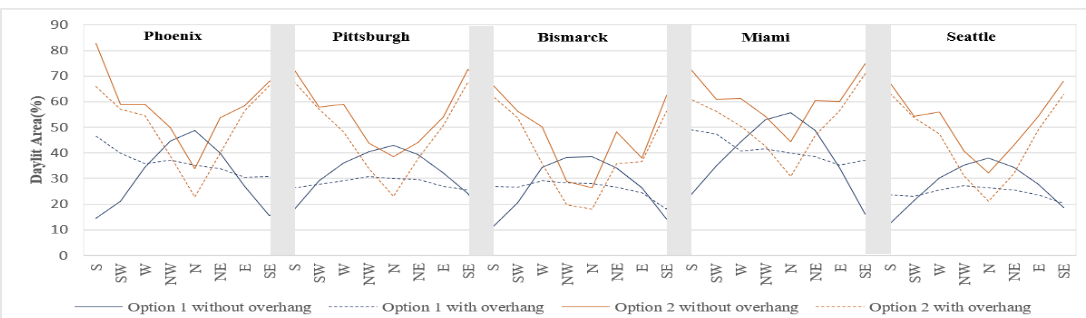

Figure 5 Option 1 vs Option 2 with consideration of overhang

DISCUSSION

The findings of this study clearly show that significantly different results can happen between the two simulation approaches for quantifying the percentage of a space that is daylit for the purpose of evaluating LEED credits. In the case of a south-facing aperture, the results in a single space can be off by as much as 500 percent with a low transmittance interior shade. As higher transmittance shades are applied, the results are more similar, but the simplified approach still exceeds the results from the sDA method for a simple sidelit space. North-facing spaces in sunnier climates general achieve higher daylight performance using sDA rather than the simplified approach. Additional investigations need to be conducted with different space and surrounding conditions, but the results of this simple study suggest that, for the simplified approach, an adjustment factor that addresses shade transmittance and another that addresses orientation could reduce a significant amount of the differences that appear between these two methods. Additional parameters could also impact performance and might be worthy of consideration in future work, such as annual sunlight hours and site latitude.

Conclusion

The results of a simulation study of a simple room with sidelighting show that the two simulation methods currently being applied in LEED (v4.1) to assess Daylight Credits provide significantly different levels of daylight coverage for a given window orientation and window shading conditions. The difference between these two approaches is largest when the transmittance of the interior shading device being applied in the sDA simulations is low, and when the shades must be closed more often to prevent direct sunlight penetration. For better agreement between these two approaches, modifications to the simplified approach must incorporate factors that address the impact of interior window shading device transmittance and possibly also how often during the year these devices must be applied. A simplified approach that is better aligned with the sDA approach should be possible with further study.

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