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A STUDY OF DAYLIGHT MODELING APPROACHES APPLLIED IN LEED

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Abstract

Across various versions of USGBC Leadership in Energy and Environmental Design (LEED), the intent of the Daylight Credit has always been to connect building occupants with the outdoors and reduce the use of electrical lighting by introducing adequate daylight into the space. However, the credit requirements and assessment methods have evolved over time. The most recent version of LEED (v4.1) 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 performs annual simulation of "Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)." sDA indicates the sufficiency of daylight inside a room and ASE shows the potential risk of visual discomfort. Option 2 adopts 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 (15 days within September 21st and March 21st). Option 3 is based on measurement of the illuminance level in the physical space rather than computer simulations. Another major difference among the options is that Option 1 fully adopts the Climate-Based Daylight Modelling (CBDM) approach, predicting hourly daylight quantity on an annual basis, including the application of interior shades when direct sunlight enters the space, while Option 2 and Option 3 measure daylight performance on some days and hours, with no consideration of interior shading. In LEED v4.1 there are some changes in performance thresholds in comparison to LEED v4 such that all options can now provide 3 points maximum. According to USGBC (E-mail interview, 2020) Option 2 is used most often among certified projects. This research focuses on the first two options in order to assess whether their results are in line with each other, and to find out whether a space which contributes to points in one option would also contribute if the other option is applied, given that Option 1 and Option 2 adopt totally different approaches. To this end, an office space model, located on the ground floor of a building with dimensions of 30 feet × 30 feet × 10 feet and a WWR of 40%, was simulated under the conditions of Option 1 and Option 2. The simulations were run in 5 different cities, considering a variety of window orientations and two different interior shading devices as well as with and without an overhang. 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.

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Introduction

Daylighting design is an integral part of sustainable architecture as it enables building occupants to be more productive and healthier and it also reduces the demand for electrical lighting; and thus, total energy consumption. Knowing how to evaluate the quantity and quality of light and how to bring an adequate amount of natural light into the space by orienting and designing the building properly is a key step that every architect needs to know. For this purpose, there are various daylight metrics and methods available which help to evaluate the quantity and quality of daylight in an enclosed space. Many studies validate and compare those metrics, but there is no general agreement on the methodologies, metrics, and interpretation of daylighting assessments.

The most recent metrics are sDA and ASE, developed by Illuminating Engineering Society (IES) in 2012 to give a better understanding of daylight performance in existing and new buildings. These metrics are adopted by green building rating systems, such as the U.S. Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) daylight credit measurement. These two metrics are used in the first option out of 3 options proposed in the latest version of LEED, Version 4 (v4) and Version 4.1 (v4.1) to achieve daylight points. While option 1 applies the most recent daylight evaluation metrics, the most widely used approach is option 2, which considers illuminance level in a point-in-time calculation. USGBC documents show 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. This data raises questions: why is option 2 more common and how does option 2 compare in terms of general agreement with option 1? Considering the option 1 and option 2 detailed methods for daylight evaluation, it seems that option 2 is an easier method to apply. Therefore, this research aims to compare the results of option 1 and option 2 in order to assess whether these two options deliver inconsistent results.

This research, firstly in Literature Review chapter, provides a detailed overview of daylight evaluation approaches, including daylight metrics and LEED daylighting performance compliance to consider the challenges of current daylight measurement methods. In Research Method chapter, a simulation setup with various daylight availability conditions that differ in location, orientation, and shading condition is developed in order to determine whether LEED (v4.1) Daylight Credit shows consistency in daylight evaluation. Then, the following chapters presents a detailed analysis of simulation results, and also investigates some modifications applied to Option 2 for better agreement between the two simulation approaches provided by LEED (v4.1) Daylight Credit.

Results of this research will provide architects, engineers and daylight designers with a comprehensive analysis of these two common methods of daylight evaluation to better estimate daylight performance in their designed spaces.

Chapter 1: Literature Review

The indoor environment, including lighting conditions, is a key factor that affects the comfort of users. Natural light provided by proper daylighting systems, has proven to be useful for the health, productivity, and performance of building occupants and it has been associated with fewer errors or defects in products, positive attitudes, reduced fatigue, and reduced eyestrain. Studies also show that the appropriate use of daylighting decreases the occurrence of headaches, SAD, and eyestrain (Edwards and Torcellini, 2002).

Daylighting is also an integral part of sustainable buildings because it is assumed to minimize the use of electricity. There are many studies on the potential energy savings over the use of daylight. With proper window design including appropriate shapes, size (window to wall ratio) and glazing types, daylight can significantly reduce the need for artificial lighting (Alhagla et al, 2019).

Based on the importance of daylighting, this literature review consists of two main parts. It starts with a general review of factors which affect daylighting during building design to consider the potential variables for the research purpose. Then, the second part is devoted to daylight evaluation methods and metrics to have a clear perspective of existing methods and metrics in terms of their accuracy and limitations. In this chapter, common daylight metrics, daylighting performance compliances, and evaluation tools are considered.

1.1. Designing for daylight

To design for daylight, it is essential to know the quantitative and qualitative definition of a well-daylit space and effective parameters in design. According to Reinhart (2014), a space which provides a task-specific amount of daylight available in the space is called daylit. This amount is due to occupant comfort and energy concerns. The following table presents IES-recommended light levels for office spaces:

Table 1. Illuminating Engineering Society's (IES) illumination recommendations for office spaces (IES Lighting Handbook)

Application – Office/Workplace	Horizontal Average (FC)*	Maintained Horizontal Range (FC)	Vertical Average (FC)	Maintained Vertical Range (FC)
Open Office (Desk)	40	30-50	-	-
Private Office (Desk)	40	30-50	-	-
Conference Room (Table)	30	15-60	-	-
White board (Reading)	-	-	15	7.5-30
White board (Presenting)	-	-	30	15-60
Presentation Screen (Projector)	-	-	1.5	1.5-6
Lunch & Break Room	15	5-20	-	-
Stairs	5	2.5-10	3	1.5-6
Corridor	5	2.5-10	3	1.5-6
Filing (Intermittent)	15	7.5-30	10	5-20
Restroom (General)	5	2.5-10	3	1.5-6
Restroom (Wash Area)	15	7.5-30	20	10-40

***Each Foot candle (FC) is 10.76 lux.**

This research studies the differences between LEED options (option 1 and option 2) for daylight credit and compares points achieved by a sample model through each option. To consider a range of conditions, the model will be examined across a range of different variables. This section considers influencing parameters in daylighting during building design in order to have a better perspective of selected variables which would affect the simulation results. All of the following parameters affect daylight performance of a space, and knowing them helps in the analysis of results.

1.1.1. Geometry properties

- **Orientation**

Littlefair (2011) points out that in the northern hemisphere, south-facing windows, in general, provide more sunlight, while north, east and west-facing windows will only receive sunlight at certain times. In a CIBSE document (1999), it is mentioned that a window wall facing within 90° of due south will provide good access to sunlight. Reinhart (2014) also notes that the maximum annual vertical radiation falls on a surface facing south. Figure 1 compares different orientations in terms of radiation level in Phoenix and Seattle. As can be seen, different orientations provide various level of radiation during a year. Overall, surfaces facing east, west, and north receive more radiation in Arizona with more sunshine hours. Seattle provides higher level of radiation in May, June, and July on vertical surfaces facing south orientation due to sun angle.

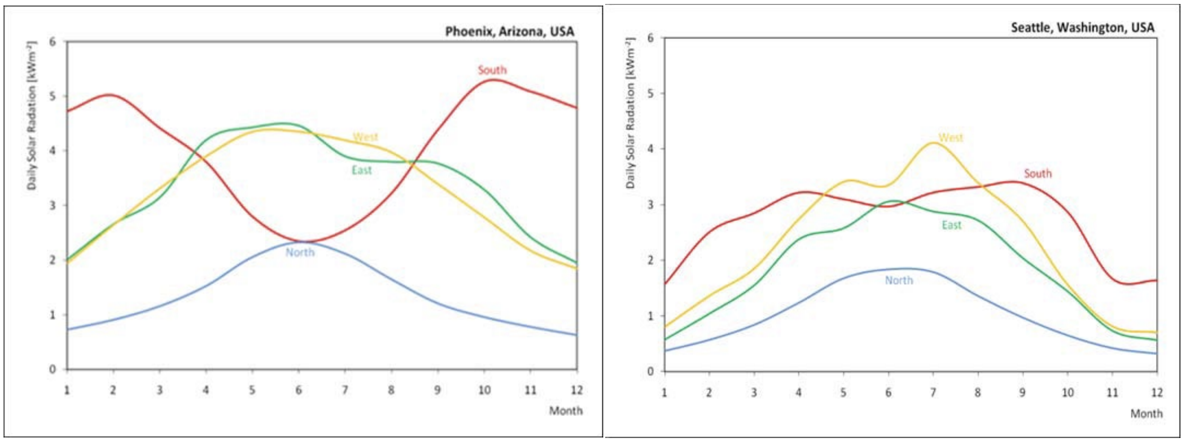


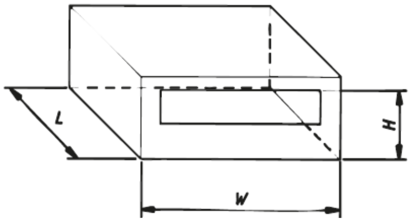
Figure 1. Mean radiation levels for different surface orientations for Phoenix and Seattle (Figure from Daylighting Handbook, Reinhart, 2014)

- **Space depth and overall size**

The British Standard (2008) recommends the following inequality for overall plan depth in a room with windows in one wall only:

$$\frac{L}{W}+\frac{L}{H}\leqslant\frac{2}{1-R_{\mathrm{b}}}$$

Where:



L is the depth of the room from window to back wall, in meters (m),
W is the width of the room, measured parallel to the window, in meters (m)
H is the height of the window head above floor level, in meters (m)
R_b the average reflectance of surfaces in the rear half of the room (away from the window) (BS 8206-2:2008).

- **Material properties**

Material choice plays an important role in daylighting design. The following list presents some factors to be considered for a better daylighting condition:

- To enhance the lighting level in corridors, LBNL (2013) recommends to use clear or translucent materials in the upper portion of partitions.
- The recommended reflectance for different elements of a space by the Illuminating Engineering Society (IES) are: ceilings >80%; walls 50%–70% (higher if wall contains window); floors 20%–40%; and furniture 25%–45%
- Choosing matte surface finishes provide good distribution of daylight without reflected glare in comparison to specular finishes (LBNL, 2013).
- Walls are recommended to be light-colored to promote brightness. Light-colored surfaces will reflect more daylight than dark surfaces (LBNL, 2013).

1.1.2. Fenestrations

In order to promote occupants' comfort, well-being, and productivity, daylight and view to outside are considered as two main criteria for window design in most green building rating systems, such as LEED certification, BREEAM, and the WELL Building Standard (U.S. Green Building Council 2019; International WELL Building Institute 2015; BREEAM International New Construction 2016).

The *Green building and LEED core concepts guide* (2014) lists lighting level and view to the outdoors as the important aspects of the indoor experience. In addition to admitting daylight, British Standard states that windows provide comfort for occupants by affording a change of scene and focus. CIBSE documents (1999) mentions the contribution of view to outside to our perception of space and it also indicates that the quality of view depends on window size, shape and location.

- **Window shape and position**

As Bokel (2007) notes, window shape and position influence the light entering the room. In another study, Fernandez (2016) addresses the impact of window placement on the uniformity of daylight in the room.

The placement of windows in the building envelope can significantly affect view out, glare and daylight distribution. High windows are most efficient at letting in daylight, particularly into the deeper part of the space, and the opening is less obstructed by other buildings, and trees. The more sky that can be seen, the better the daylight, and high windows are best for this (CIBSE, 1999). In a study that considered three different placements of low, middle, and high windows as shown in the figure, Bokel (2007) noted that the lower window is worst for daylighting purpose. Windows with high sills transmit daylight deeper into rooms (Altan et al, 2015).

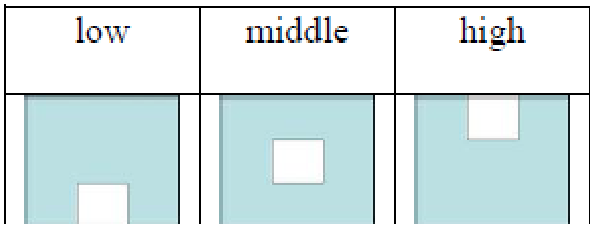


Figure 2. Different window positions (Bokel, 2007)

Alhagla (2019) notes that wider windows provide more uniform light distribution and hence, are recommended in places where functional activity requires uniform spread of light; on the other hand, LBNL (2013) mentions the light/dark contrast created by vertical windows, in other words, tall and narrow windows cause glare issues more that the long and wide windows with the same area.

- **Window size**

Ochoa et al (2012) states that with proper window size, the amount of daylight entering a space can dramatically increase, but window size has to be optimized for more than one objective, due to its influence on energy consumption and visual comfort. Alhagla et al (2019) found that windows with more window-to-wall ratio (WWR) result in more illuminance and a better daylight distribution in a room but the larger the window, the more important glazing type is to control glare and solar heat gain. PNNL-20380 (2007) considers “typical” building envelope components for constructed buildings after 1980, and finds the average of 19%-54% WWR for office buildings.

- **Window components: glazing and shading**

LBNL (2013) lists a number of glazing properties to consider when choosing glazing material:

Table 2. Glazing properties

Visible Transmittance	The percentage of light in visible portion that passes through a glazing material. Higher visible transmittance results in more illuminance, however, they can cause glare issues (LBNL, 2013).
U-Value	a measure of heat transfer through the glazing due to a temperature difference between the indoors and outdoors. This property is important for thermal resistance of the window (LBNL, 2013).
Visible Reflectance	The percentage of visible light that is reflected from the glazing. High reflectance comes with low visible transmittance and its possible problems (LBNL, 2013).
Shading Coefficient (SC)	The ratio of solar gain passing through a glass to that of double-strength clear glass. To maximize daylight, shading coefficient should be high because this means that visible transmittance is also high (Taylor et al, 2009; LBNL, 2013).
Solar Heat Gain Coefficient (SHGC)	The ratio of total transmitted solar heat to incident solar energy. SHGC is mostly used in cooling load calculations and closely related to visible transmittance values (LBNL, 2013).

Shading devices are also essential for solar gain reduction. There are a variety of internal and external shading devices for this purpose. External shading is typically more effective than interior systems in reducing solar heat gain.

Philips (2004) lists the external shading options available for use in buildings:

- Overhangs and canopies
- Continental shutters, and awnings
- Light shelves
- Fixed and movable louvres
- Egg-crate louvres
- External roller blinds

Philips (2004) also lists internal shading options and he points out that internal shadings are less efficient than external ones in controlling heat gain, since extracting the heat which has already entered the room is more difficult, however, internal devices are less vulnerable and easier to maintain and clean, so that all factors should be taken into consideration when it comes to decision making. The following are some of the options available:

- Curtain
- Venetian blind
- Prismatic glazing panels (Philips, 2004)

1.1.3. Exterior context

- **Daylight availability**

Ruck (2000) notes that daylight strategies are dependent on the availability of sunlight, which is affected by the latitude of the building site and the surrounding conditions of the building, e.g., the presence of obstructions. Latitude determines the length of daytime and solar availability at different seasons of the year, as well as the maximum and minimum solar elevation. Reinhart (2014) states that latitudes below 50° have the potential to access daylight for 80% of annual core commercial hours, and that 93% of the world's population live at latitudes below 50°.

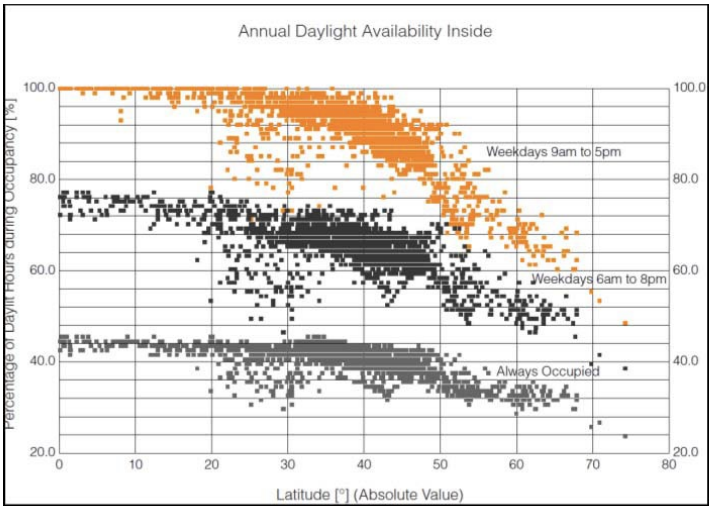


Figure 3. Annual daylight availability inside (Figure from Daylighting Handbook, Reinhart, 2014)

Reinhart (2014) clustered North America into five daylighting zones based on daylight autonomy distributions in a south-facing office in 186 sites across the United States and Canada.

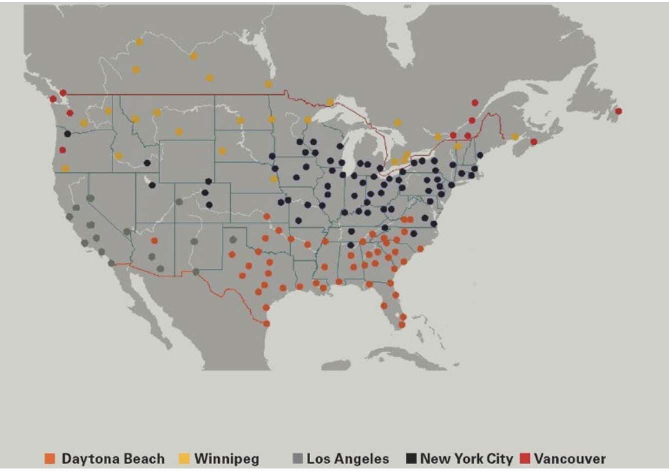


Figure 4. North America daylighting zones (Figure from Daylighting Handbook, Reinhart, 2014)

Daylighting design is also influenced by climate; thus, knowing the prevailing climatic conditions, particularly ambient temperatures and sunshine probability, is a basic step in daylight design. Studying both climate and daylight availability at a construction site is key in daylighting design. The daylighting design strategy for the building should address these conditions.

The difference between summer and winter becomes greater at high latitudes. Winter daylight levels are low at high latitudes, therefore, designers' main goal is maximizing daylight penetration into the building; redirection of daylight into buildings from the brightest regions of the sky is an appropriate strategy at these latitudes. By contrast, "in the tropics where daylight levels are high throughout the year, the design focus is usually on restricting the amount of daylight entering the building" (Ruck, 2000).

- **Building site and obstructions**

Ruck (2000) believes that effective daylight design starts at site layout phase, before building and window design, since the sky is usually obstructed to some extent by surrounding buildings and vegetation. The amount of received light and its distribution will be affected by surrounding obstructions (CIBSE, 1999).

Littlefair (2011) states that obstruction can be quantified in a number of ways in order to evaluate the entering daylight. The obstruction angle is one of the indicators of obstruction quantification. Obstruction angle is the angle the obstruction makes from the center of the window, measured from the horizontal and it is related to visible sky angle (θ) (Figure 5). So, the taller and nearer obstructions result in less received light, but the width of the obstruction is also an influencing parameter. Narrow obstructions allow entering daylight from its sides.

Vertical sky component (VSC) is an alternative approach to check access to light from the sky. Littlefair (2011) defines VSC as "the ratio of the direct sky illuminance falling on the vertical wall at a reference point (usually the center of the window), to the simultaneous horizontal illuminance under an unobstructed sky". The ratio is expressed as a percentage with a maximum value of almost 40% for a completely unobstructed vertical wall.

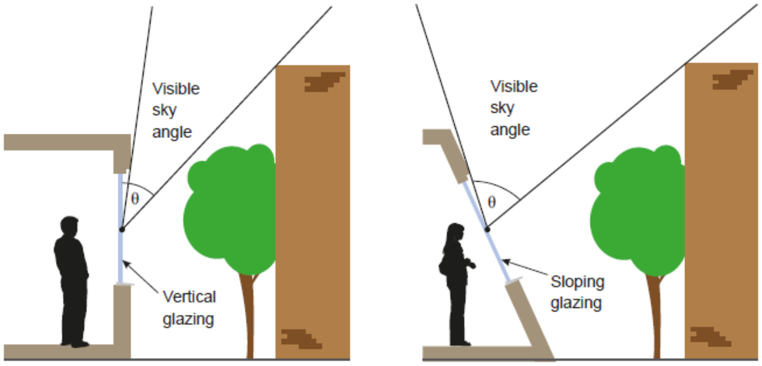


Figure 5. visible sky angle (Littlefair, 2011)

Table 3. Daylight condition based on obstruction angle (Littlefair, 2011)

Obstruction angle	**Daylight condition**
Less than 25° or θ greater than 65° (VSC at least 27%)	Conventional window design will usually give a reasonable result
Between 25° and 45° or θ between 45° and 65° (VSC between 15% and 27%)	Special measures (larger windows, changes to room layout) are usually needed to provide adequate daylight
Between 45° and 65° or θ between 25° and 45° (VSC between 5% and 15%)	It is very difficult to provide adequate daylight unless very large windows are used
Greater than 65° or θ less than 25° (VSC less than 5%)	It is often impossible to achieve reasonable daylight, even if the whole window wall is glazed

1.2. Methods for daylighting design evaluation

1.2.1. Daylight performance evaluation

A variety of daylight metrics have been developed over the years to evaluate the daylight performance in a space. These metrics have evolved from single sky metrics such as daylight factor to climate-based metrics which consider all sky conditions. A number of these metrics are used in different building rating systems. An overview of some of the main daylight metrics currently in use is provided in this section.

- **Daylight Factor**

The daylight factor (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) expressed as percent.

$DF = E_{indoor} / E_{outdoor} * 100\%$

The recommended thresholds for DF are between 2% and 5%. An average daylight factor of 5% or more ensures that a space looks substantially daylit and an average daylight factor below 2% represents that electric lighting is likely to be in frequent use. The DF can be affected by design variables like the window size, the transmittance of the glazing material, and the reflectance of surfaces, etc. (CIBSE, 1999).

The limitation of DF is that building location, orientation, season and time of day are excluded from the calculation, so the DF would have the same result whether the building has a north-facing window in rainy Seattle or south-facing window in sunny Phoenix (Hu, et al, 2014). Movable shading devices also are not taken into consideration in daylight factor calculations, since they are not needed under overcast sky conditions. One of the main consequences of these limitations is that daylight factor cannot help to analyze glare-associated problems (Reinhart et al, 2006).

- **Daylight Autonomy (DA)**

DA is defined as the percentage of the year when the illuminance level at an analysis point is above the target threshold (Acosta et al, 2019). For example, DA_{300} means the percentage of occupied hours greater than or equal to 300 lux.

DA is a climate-based metric and uses real weather data and this is its advancement over DF. Daylight autonomy also has limitations. Daylight autonomy considers no account of thresholds for lower and upper limits of daylight suggesting visual discomfort (Nabil et al., 2006).

- **Useful Daylight Illuminance (UDI)**

Useful daylight illuminance (UDI) is defined as the percentage of occupied time that a point in the space falls in a target illuminance range. The range that defines the threshold limits of useful daylight illuminance is based on reported occupant preferences in daylit offices. The different ranges for UDI are defined below:

1. Less than 100 lux is insufficient;
2. Within the range of 100~2000 lux is defined as useful;
3. Greater than 2000 lux may cause discomfort and glare. (Nabil et al., 2006).

- **Continuous Daylight Autonomy (cDA)**

Continuous Daylight Autonomy (cDA) is a modification of daylight autonomy, proposed by Rogers in 2006. Continuous Daylight Autonomy gives partial credit to values below the defined threshold. For example, when 500 lx are required to have a daylit space and 400 lx are provided by daylight at a given time step, a partial credit will be given to that time step as 400 lx / 500 lx = 0.8. (Reinhart et al., 2006:11). This metric is more flexible and indicates that even a partial contribution of daylight toward space illumination is still beneficial (Reinhart et al., 2006).

- **Spatial Daylight Autonomy (sDA)**

The Illuminating Engineering Society (IES) reviewed and assessed the above metrics, and introduced two new metrics, which the LEED V4 and v4.1 credit apply, Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). Report of these two values together helps to evaluate the sufficiency of daylight and the risk of visual discomfort

IES-LM-83 defines Spatial Daylight Autonomy as a dynamic metric describing annual sufficiency of ambient light levels in interior environments. It is defined as the percent of an analysis area (the area where calculations are performed - typically across an entire space) that meets a minimum daylight illuminance level for a specified fraction of the operating hours per year. The illuminance level and time fraction are included as subscripts, as in $sDA_{300,50\%}$. The sDA value is expressed as a percentage of the analysis area.

IES recommends that 55% or more of the regularly occupied area meets or exceeds an illuminance threshold of 300 lux for at least 50% of the total occupied hours of the year.

- **Annual Sunlight Exposure (ASE)**

Annual Sunlight Exposure (ASE) is a metric that evaluates the potential for visual discomfort due to direct sunlight penetration, measuring the percent of the floor area that exceeds 1000 lx from direct sunlight for more than 250 hours per year, before any operable blinds or shades are deployed to block sunlight (LM83-12).

1.2.2. LEED Daylighting performance compliance

An overview of the performance compliance approach available for documenting daylighting performance for LEED projects is presented below.

- **LEED 2009**

Daylight credit in LEED 2009 aims to provide building occupants with a connection between indoor spaces and the outdoors through the introduction of daylight and views into the regularly occupied areas of the building. There are four options that projects can choose to achieve this credit:

Option 1, Simulation: Projects are compliant when demonstrated through computer simulations that 75% or more of the applicable spaces achieve daylight illuminance levels of a minimum of 10 footcandles (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 should also be provided for the project, demonstrating compliance with the minimum 10 fc (110 lux) requirement (LEED v3 BD+C, 2009).

Option 2, Prescriptive Calculations: Demonstrate that all regularly occupied spaces have daylight zone calculations. For side-lighting zones, the daylighting zone values should be between 0.15 and 0.18, calculated as a product of the visible light transmittance (VLT) and window-to-floor area ratio (WFR). The project should also provide glare control devices demonstrating compliance with the minimum 0.15 criteria. For top-lighting zones, projects are compliant when skylight coverage is between 3% and 6% of the total floor area. The skylight must have a minimum 0.5 VLT and 90% or more haze value when a skylight diffuser is used (LEED BD+C, 2009).

Option 3, Measurement: Demonstrate that a minimum daylight illumination level of 10 fc (110 lux) and a maximum of 500 fc (5,400 lux) has been achieved in the applicable spaces through records of indoor light measurements. Glare control devices should also be provided for the project, demonstrating compliance with the minimum 10 fc (110 lux) requirement (LEED v3 BD+C, 2009).

Option 4, *combination*: A combination of options can be used to document the minimum daylight illumination in space (LEED v3 BD+C, 2009).

- **IES LM-83-12**

The Illuminating Engineering Society (IES) introduced two new CBDM metrics, Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), in 2012. LEED v4 and v4.1 use these two metrics in the Option 1 compliance path for the Daylight Credit. IES-LM-83 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-LM-83-12).

- **LEED v4**

The intent of the daylight credit in LEED v4 is increasing daylight in the space to provide a connection between building occupants and the outdoors, supporting circadian rhythms and reducing electrical lighting consumption (LEED v4 BD+C, 2014). There are three options for compliance:

Option 1, Simulation: projects need to demonstrate through annual computer simulations that 55% or more of the regularly occupied floor area achieve 300 lux for at least 50% (sDA) of the total occupied hours of the year, and *demonstrate through annual computer simulations that annual sunlight exposure of no more than 10% of occupied floor area* receiving 1000 lux for 250 hours (ASE).

Table 4. Points for daylit floor area: Spatial daylight autonomy (Option 1) (LEED v4 BD+C, 2014).

New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses and Distribution Centers, Hospitality		**Healthcare**	
sDA (for regularly occupied floor area)	points	sDA (for regularly occupied floor area)	points
55%	2	75%	1
75%	3	95%	2

Option 2, Simulation: Compliant projects need to *demonstrate through computer modeling that illuminance levels of 75% or more of the regularly occupied floor area is between 300 lux and 3,000 lux for 9 a.m. and 3 p.m., both on a clear-sky day at the equinox (15 days within September 21st and March 21st).*

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 in this research.

Table 5. Points for daylit floor area: Illuminance calculation (Option 2) (LEED v4 BD+C, 2014).

Percentage of regularly occupied floor area	**points**
75%	1
90%	2

Option 3, Measurement: Compliant projects need to show that 75% or more of *regularly* occupied floor area achieve 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 one can be in any regularly occupied month, and the second one, however, needs to be taken at least 5 months later (LEED v4 BD+C, 2014).

Table 6. Points for daylit floor area: Measurement (Option 3) (LEED v4 BD+C, 2014)

New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses and Distribution Centers, Hospitality		**Healthcare**	
Percentage of regularly occupied floor area	points	Percentage of regularly occupied floor area	points
75%	2	75%	1
90%	3	90%	2

Among the three options, option 1 potentially provides more points than option 2 due to a greater maximum point value. Option 2 only provides 2 points maximum, whereas option 1 provides 3 points maximum. In comparison to option 3, option 1 can be less time consuming for documentation, since option 3 measures physical daylighting in a space at two times of year, 5 months apart from each other. In addition, option 1 fully adopts the Climate-Based Daylight Modelling (CBDM) approach, predicting hourly daylight quantity on an annual basis, while option 2 and option 3 measure daylight performance on certain days and hours (Hu et al, 2014).

- **LEED v4.1**

As stated by USGBC, the daylight credit in LEED v4.1 has the intent “to connect building occupants with the outdoors, reinforce circadian rhythms, and reduce the use of electrical lighting by introducing daylight into the space” (LEED v4.1 BD+C, 2019). LEED v4.1 is generally similar to LEED v4 in approaches, but there are some updates in performance thresholds. As mentioned before, Option 1 in LEED v4 provides more points than Option 2, but in LEED v4.1 all the options provide 3 points maximum. We can also see some changes in minimum threshold of area percentage to achieve points, and it seems that LEED v4.1 has made achieving points easier. In LEED v4, projects had to demonstrate that 55% or more regularly occupied floor area achieve 300 lux for at least 50% of the total occupied hours of the year to achieve points in option 1, but LEED v4.1 has decreased the minimum percentage area to 40% and option 2 has changed it from 75% to 55%.

The options adopted by LEED v4.1 are the same as LEED v4, but there are some differences in points awarded.

Option 1, simulation: Compliant projects need to perform annual computer simulations for spatial daylight autonomy$_{300/50\%}$ (sDA$_{300/50\%}$), and annual sunlight exposure$_{1000,250}$ (ASE$_{1000,250}$) as defined in IES LM-83-12 for each regularly occupied space.

Table 7. Points for Option 1 (LEED v4.1 BD+C, 2019)

	New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses and Distribution Centers, Hospitality	**Healthcare**
The average sDA$_{300/50\%}$ value for the regularly occupied floor area is at least 40%	1 point	1 point
The average sDA$_{300/50\%}$ value for the regularly occupied floor area is at least 55%	2 points	2 points
The average sDA$_{300/50\%}$ value for the regularly occupied floor area is at least 75%	3 points	Exemplary performance
Each regularly occupied space achieves sDA$_{300/50\%}$ value of at least 55%	Exemplary performance or 1 additional point if only 1 or 2 points achieved above.	Exemplary performance or additional point if only 1 point achieved above.

Option 2, simulation: projects need to demonstrate through computer simulations that 55% or more of *each regularly occupied space* achieve illuminance level between 300 and 3000 lux at 9 a.m. and 3 p.m. on a clear-sky day at the equinox.

Table 8. Points for Option 2 (LEED v4.1 BD+C, 2019)

New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses and Distribution Centers, Hospitality		**Healthcare**	
Percentage of regularly occupied floor area	points	Percentage of regularly occupied floor area within perimeter area	points
55%	1	55%	1
75%	2	75%	2
90%	3	90%	Exemplary performance

Option 3, Measurement: Demonstrate each regularly occupied space achieves illuminance levels between 300 lux and 3,000 lux. Spaces with view-preserving automatic (with manual override) glare-control devices may demonstrate compliance for only the minimum 300 lux illuminance level.

Table 9. Points for Option 3 (LEED v4.1 BD+C, 2019)

New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses and Distribution Centers, Hospitality		**Healthcare**	
Percentage of regularly occupied floor area	points	Percentage of regularly occupied floor area within perimeter area	points
55% at one time in the year	1	55% at one time in the year	1
75% at two times in the year	2	75% at two times in the year	2
90% at two times in the year	3	**90**% at two times in the year	Exemplary performance

1.2.3. Performance modeling tools

There are several simulation tools that can be used to comply with LEED v4.1 for daylight credit. The following considers some of these tools and their calculation methods in order to have a better perspective of daylight calculations and to choose an efficient tool for the simulation purpose of this research.

- **RADIANCE**

RADIANCE is a free ray-tracing tool developed by Ward in 1994 at the Lawrence Berkeley Laboratory (LBL) in California and the Ecole Polytechnique Federale de Lausanne (EPFL) in Switzerland (Ward, 1994). It has been validated many times by numerous empirical studies (Subramaniam, 2017). RADIANCE is able to model a wide range of material properties, including diffuse, specular and semi-specular reflection and transmission, refraction in dielectrics, patterns and textures, material mixtures, and general bi-directional reflection/transmission functions (Greenup et al.,2001). The input required for simulation with RADIANCE includes geometry, materials, and light sources in a scene. The following is an overview of the various simulation methods that RADIANCE uses.

Daylight Coefficients (The Two-Phase Method)

Tregenza and Waters (1983) proposed the concept of daylight coefficients. In this method, the celestial hemisphere is divided into a series of discrete sky segments and the total illuminance at a point in the room is the sum of the illuminance from discrete sky segments. Each sensor's position within a given environment and orientation are taken into consideration. Typical Meteorological Year (TMY) weather data is the source of luminance values for the skies used in the Daylight Coefficient Method (Bourgeois et al., 2008; Subramaniam, 2017). The following equation defines the daylight coefficient.

$$DC_{\alpha}(x) = \frac{E_{\alpha}(x)}{L_{\alpha}\Delta S_{\alpha}}$$

Where:

x	sensor point,
S_α	sky segment,
ΔS_α	angular size of S_α,
$E_\alpha(x)$	illuminance at x due to S_α,
$L\alpha$	luminance of S_α

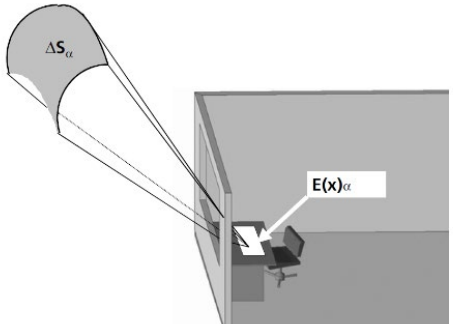


Figure 6. Definition of a daylight coefficient (Subramaniam, 2017)

Subramaniam (2017) notes that even complex types of glazing and shading systems can be incorporated into Daylight Coefficient based calculations, however, this method is most suitable for models with simple glazing and shading systems.

The three-phase method

Subramaniam (2017) also states that the Three-Phase Method is suitable for annual or point-in-time parametric daylighting simulations with Complex Fenestration Systems. The Three-Phase Method calculation is based on the following equation.

E=VTDS

Where:

V	view matrix,
D	exterior daylight matrix,
S	sky matrix,
T	Transmission matrix

The four-phase method (with F-Matrix)

The Four-Phase Method has an additional matrix (F-Matrix) to account for flux-transfer in parametric modeling of external and non-coplanar shading systems. The Three-Phase Method matrix equation can be rewritten for the Four-Phase Method as (Subramaniam, 2017):

$$E=VTFDS$$

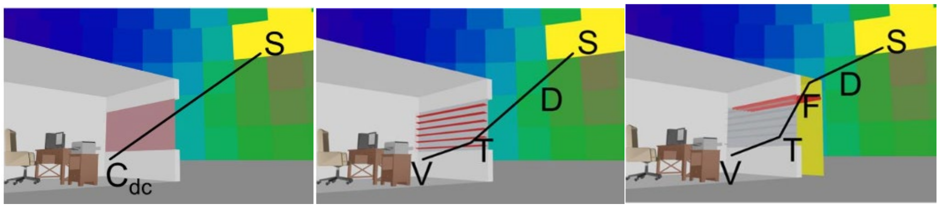


Figure 7. Daylight Coefficient Method, Three-Phase Method, Four-Phase Method (Subramaniam, 2017).

The five-phase method

McNeil (2013), in another study, points out that The Five-Phase Method is an extension of The Three-Phase Method, improving the direct solar component to achieve better accuracy of the distribution of direct sunlight in a room for complex glazing systems.

$$E=VTDS - V_d T D_d S_{ds} + C_{ds} S_{sun}$$

Where:

V= View matrix,

V_d= Direct only view matrix

T= Transmission matrix,

D=Daylight matrix,

D_d=Direct only daylight matrix,

C_{ds}=Coefficient matrix for direct sun relating radiance of many sun positions to direct illuminance at a sensor point using a BSDF with proxy geometry or a variable resolution BSDF material.

S=Sky matrix,

S_{ds}=Sky matrix containing only the sun luminance (no sky luminance)

S_{sun}=Direct sun matrix containing the radiance and position of the sun.

- **DAYSIM**

DAYSIM is a daylighting analysis tool that runs annual daylight calculations. DAYSIM uses a combination of the RADIANCE ray trace and Daylight Coefficient methods using a Perez sky model. A description of the study pace, including geometry and the materials in the form of regular RADIANCE input files and light sources are the required inputs for a DAYSIM simulation. Daylight sources must be provided at each time step and DAYSIM uses the Perez sky luminous efficacy and sky luminance distribution sky model for this purpose (Walkenhorst et al., 2002). The simulation outcomes include Daylight Autonomy, Useful Daylight Illuminance, lighting energy consumption with shading systems (Jakubiec et al., 2012).

- **DIVA**

DIVA is a plug-in for Rhinoceros, it was initially developed by the Graduate School of Design at Harvard University and now is administered by Solemma LLC. DIVA-for-Rhino permits users the ability to run a series of daylighting and energy modeling evaluations, including radiation maps, radiance renderings, glare analysis, and single thermal zone energy and load calculations. DIVA can also be used together with another plug-in for Rhino called Grasshopper. DIVA uses RADIANCE, DAYSIM and Energy Plus as calculation engines. It adopts RADIANCE backward ray tracing for Daylight Factor and scene visualization calculations, DAYSIM is used for annual-climate based metrics simulation, and Energy Plus is used for building energy use (Solemma, 2020; Dutra de Vasconcellos, 2017).

- **Ladybug Tools**

Ladybug, Honeybee, and Honeybee [+] (HB[+]) are open-source plug-ins for Grasshopper. Using an EnergyPlus Weather file (EPW), Ladybug provides a variety of climate graphics, including sun-path, wind-rose, radiation analysis, shadow studies, and view analysis. It helps designers to make environmentally-conscious decisions during the early stages of design

Honeybee is most relevant during mid and later stages of design. Honeybee links EnergyPlus, RADIANCE, DAYSIM, and OpenStudio with Grasshopper for daylight simulation and building energy analysis (ladybug.tools, 2020).

HB[+] uses Radiance-based workflows for daylighting simulations and it provides four simulation methods, including

- **LightStanza**

LightStanza is a RADIANCE-based daylight simulation tool. LightStanza can perform annual and point in time calculations. The outputs include daylight distribution, annual metrics (SDA + ASE), false-color view renderings and glare studies (LightStanza, 2020).

1.2.4. LEED v4.1 Option 1 and Option 2 simulation procedure

It is essential to consider the option 1 and option 2 simulation procedures in detail to better understand the possible differences between their results. LEED v4.1 refers to LEED v4 *Reference Guide* (2014) for the simulation procedures of Option 1 and Option 2.

- **LEED v4.1 Option 1 simulation procedure**

The geometry of the space should first be accurately modeled, based on the modeling methodology outlined in IES LM-83-12. The model should include exterior obstructions, blinds or shades, permanent interior obstructions, and material detail of interior/exterior surfaces.

The analysis period is 10 hours per day per common working hours and it should be done from 8AM to 6PM local time for a full calendar year.

The analysis area should be covered with a calculation grid at a height of 30” above finished floor with a maximum spacing of 24” and the offset from the wall should be within 12” to 24”.

The interior surfaces reflectance should be modeled by either measured data, or the IES LM-83-12 recommended values (20% floor, 50% walls, 70% ceiling, 50% furniture).

The climate modeling for the sDA and ASE calculation is based on hourly TMY weather data of the nearest available weather station.

For the sDA calculation, all the image preserving exterior windows should be modeled with interior blinds both up and down, and the blinds should be closed whenever more than 2% of the analysis points receive direct sunlight. IES LM83-12 defines direct sunlight as an interior measurement of 1000 lux or more of direct beam sunlight that accounts for window transmittance but excludes the effect of any blinds or shades, with no contribution from reflected light, i.e. zero bounces, and no skylight contribution. In terms of optical properties of blind/shades, IES LM-83-12 suggests to use the Bidirectional Transmittance or Scattering Function (BSDF) data, and when it is not available the shades can be modeled by their Visible Light Transmission (VLT), which combines the specular and diffuse transmittance. If the shade material is unknown, IES LM-83-12 recommends applying a 5% diffuse VLT with no specular transmittance. In an ASE simulation, the shades or blinds should be left open, and only overhangs or other fixed shading devices should be included in the model.

- **LEED v4.1 Option 2 simulation procedure**

The simulation methodology for the point-in-time simulation is similar to that described in IES LM-83-12 for sDA and ASE. Firstly, the building geometry should be modeled with the recommended level of detail in IES LM-83-12. All the recommendations for surface reflectance, exterior obstructions, and furniture and partitions work for this option, too.

Analysis period is different from option 1. Analysis should be performed at 9 A.M. and 3 P.M. on the equinox (15 days within September 21st and March 21st).

The analysis area should cover all regularly occupied floor area. The calculation grid and the location of the analysis points are same as option 1 and recommended values in IES LM-83-12 for sDA and ASE should be used.

The interior surfaces reflectance should be modeled by either measured data, or the IES LM-83-12 recommended values, the same as option 1 (20% floor, 50% walls, 70% ceiling, 50% furniture).

For climate modeling, TMY weather data of the nearest available weather station should be used. The simulation should be performed under the clearest sky condition. For this purpose, from the TMY file, the day within 15 days of September 21 and March 21 that has the clearest sky condition (total sky cover at its lowest value) at 9 A.M should be selected. The average of these two values is the input of the direct horizontal irradiance for the 9 A.M. simulation. Also, the average of the diffuse horizontal irradiance (Wh/m2) values at 9 A.M. for the day selected in September and at 9 A.M. for the day selected in March should be used in the 9 A.M. simulation as the diffuse horizontal irradiance input. This procedure should be repeated for 3 P.M.

The following table presents a comparison of option 1 and 2 regarding required data input and thresholds:

Table 10. Comparison of option 1 and option 2 simulation methods

	sDA	ASE	Option 2
Analysis period	10 hours per day (8AM to 6PM) Whole year	10 hours per day (8AM to 6PM) Whole year	at 9 A.M. and 3 P.M. on the equinox
Illuminance threshold	300 lx	1000 lx	Between 300 lx and 3000 lx
Analysis area	Regularly occupied work areas		
Analysis Points	No greater than 2' by 2' spacing, 1' to 2' offset from the walls, at 30" in height		
climate modeling	hourly TMY weather data	hourly TMY weather data	hourly TMY weather data for clearest sky condition within 15 days of September 21 and March 21
Blinds/Shades Operation	Close whenever more than 2% of the analysis points receive direct sunlight	Left open	No mention to any essential blind/shade

Summary and expected outcome of thesis

Reviewing various daylight assessment methods and metrics, this research aims to analyze the LEED daylight credit (v4.1) as one of the most common rating systems. LEED v4.1 provides 3 options for daylight credit, but since option 3 is a time-consuming method, performed after completion of a project, this research focuses on option 1 and option 2. According to USGBC, option 2 has been used by 62% of certified projects under LEED v4, regardless of the fact that projects can receive only 2 points maximum in option 2, while they could receive 3 points in options 1 and 3. This research explores the reason behind the popularity of option 2 compared to option 1.

Since the two simulation-based approaches, Options 1 and 2, used in LEED v4.1 vary significantly in their approach, this study focuses on a study intended to assess whether the results from these options are aligned. For example, option 1 demonstrates an annual run, while option 2 performs simulations on specific days and times. The other major difference is the requirement of blinds in the option 1 sDA calculation, while they are not addressed in option 2. It is reasonable to conclude that there is a possibility of discrepancies in the results of the two options. 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. Evaluation and prediction of daylight performance in a space is an important matter for architects and daylight designers, and the results of this research will give them a better perspective on the two available methods for LEED daylight assessment.

Chapter 2: Research Methodology

According to the literature review, the two simulation-based approaches, Options 1 and 2, used in LEED v4.1 vary significantly in their approach. Therefore, it is likely that LEED (v4.1) Option 1 and Option 2 show inconsistent results. In this chapter, a simulation setup with various daylight availability conditions that differ in location, orientation, and shading condition was developed to in order to determine whether Option 1 and Option 2 show aligned results.

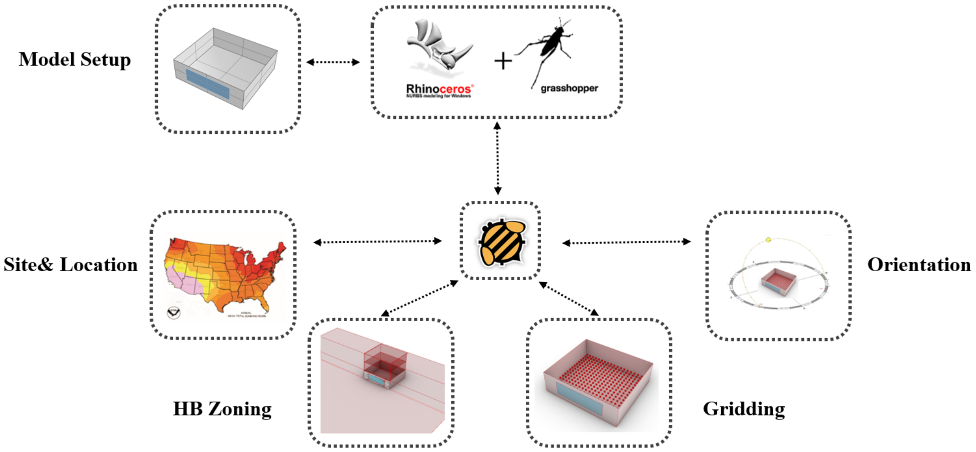


Figure 8. Overview of research method

2.1. Simulation setup

2.1.1. Sites and locations

Given that Reinhart (2014) clusters North America into five daylight zones, five cities were selected in different daylight zones of the United States with various sunshine conditions, covering the latitude range 37° to 48° used in the supporting research for IES LM 83-12.

Table 11. Five cities selected for research

Location	Latitude	Annual mean total sunshine hours (US Department of Commerce, 2005)
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

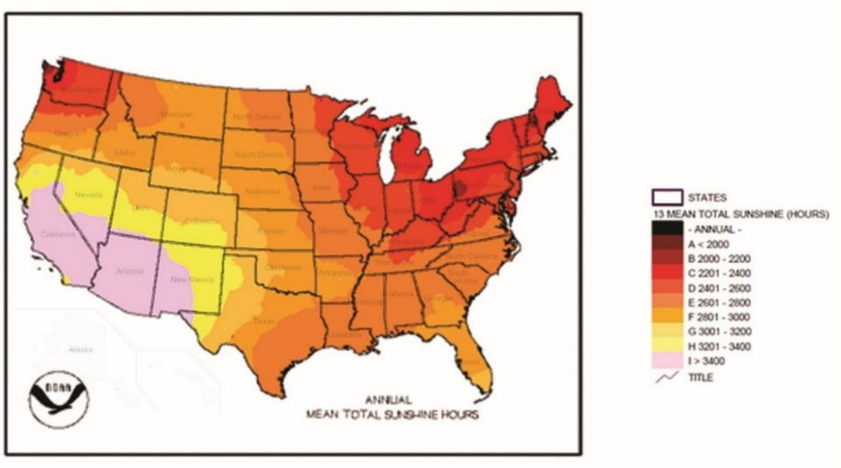


Figure 9. Sunshine hours map (US Department of Commerce, 2005)

2.1.2 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 30 feet × 30 feet × 10 feet. A single wall includes a window with a Window-to-Wall Ratio (WWR) of 40 percent based on literature review findings that shows the average of 19%-54% WWR for typical office buildings (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 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 reflectance and window properties are shown in following tables:

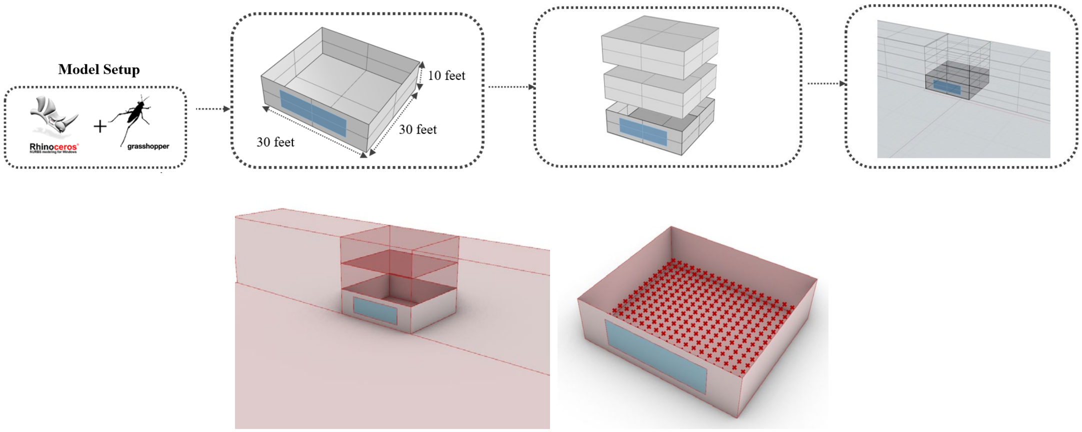


Figure 10. Test model for research

Table 12. Material properties of the model

Finished surface	Surface reflectance
Ceiling	80%
Wall	50%
Floor	20%
Ground	15%
Exterior wall	30%
Overhang	50%

Table 13. Material properties of the window

Window element	Optical properties
glazing	60% VLT

Table 14. Roller shades parameters

Diffuse VLT	**5%**
Specular transmittance	0%

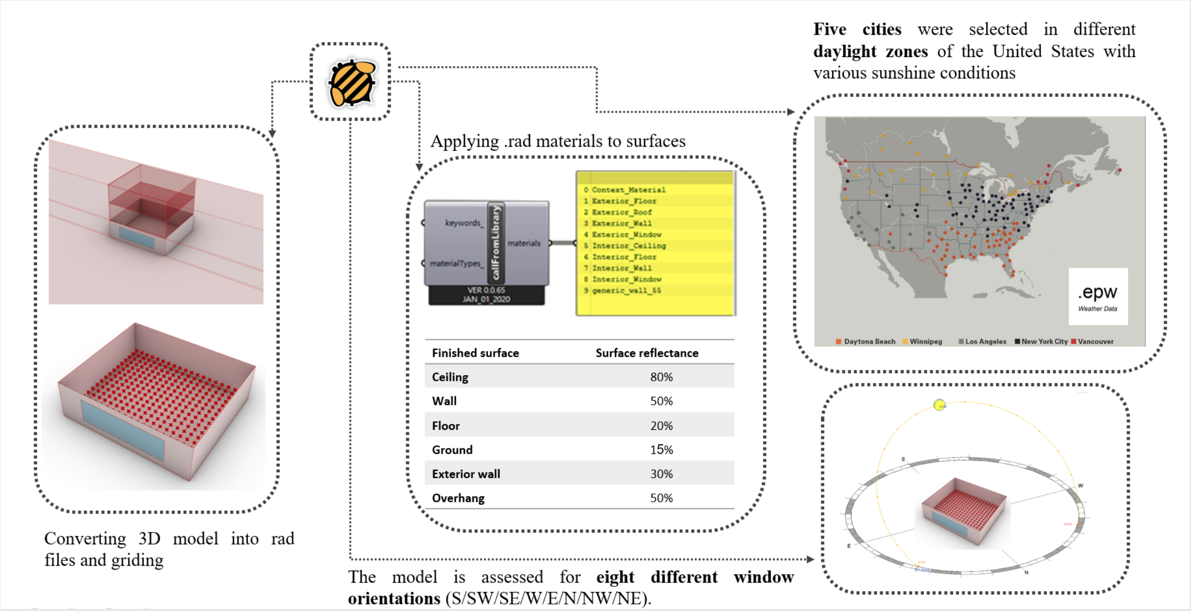
2.2. Simulation method

Based on simulation methods from the LEED *Reference Guide for Building Design and Construction* (2014) and IES LM83-12 which are explained in the literature review, the methods are adopted in accordance with the capabilities of the selected simulation tool. Each option is simulated in five cities and the model is rotated into eight orientations. For both options, TMY weather data of the nearest station is used.

2.2.1. Option 1:

Option 1 is based on sDA simulations. To calculate sDA in HB[+],windows must be modeled with interior shading lowered whenever more than 2 percent of the analysis grid points receive direct sunlight. 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.

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.



Five cities were selected in different **daylight zones** of the United States with various sunshine conditions

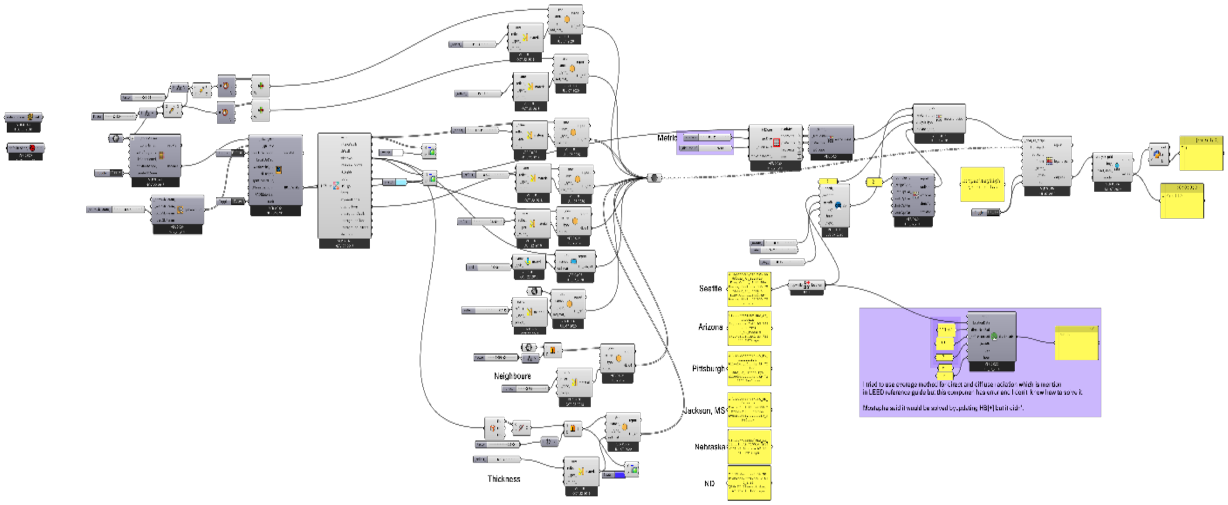
Applying .rad materials to surfaces

Finished surface	Surface reflectance
Ceiling	80%
Wall	50%
Floor	20%
Ground	15%
Exterior wall	30%
Overhang	50%

Converting 3D model into rad files and griding

The model is assessed for **eight different window orientations** (S/SW/SE/W/E/N/NW/NE).

Figure 11. Simulation Procedure for both options



I tried to use average method for direct and diffuse radiation which is mention in LEED reference guide but this component has error and I don't know how to solve it.

Mostapha said it would be solved by updating HB[+] but it didn't.

Figure 12. HB[+] algorithm

2.2.2. 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 percentage of points falling within the illuminance range across the four conditions.

2.2.3. HB [+] simulations

Honeybee [+] 0.0.06, an open-source plug-in for Grasshopper that 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. Ambient bounces (ab) describe the number of diffuse inter-reflections that will be calculated before a ray path is discarded. This parameter significantly increases the required calculation time. HB[+] has three levels of complexity for simulation, including low, medium, and high. High complexity was applied to the 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

Summary

This chapter provided a detailed overview of simulation methods for Option 1 and Option 2 based on the LEED *Reference Guide for Building Design and Construction* (2014) and IES-LM83. The next chapter presents the simulation results and compares Option 1 and Option 2 in terms of the percentage of daylit area that contribute to the attainment of LEED daylight credits and the LEED points that are associated with this coverage level. The simulation results are considered in several scenarios with various daylight availability conditions that differ in location, orientation, and shading condition to consider whether Option 1 and Option 2 show aligned results.

Chapter 3: Results and Discussion

In this chapter, simulation results for Option 1 and Option 2 as used to evaluate daylight credits for USGBC LEED are presented in detail. Calculations are done in five cities located in five daylighting zones with various annual sunlight hours as described in the previous chapters, and the model is rotated toward eight orientations due to present different daylight conditions and availability as discussed in literature review.

3.1. Results of Option 1

Table 15 shows that in Arizona, which has the highest annual total sunshine hours of the selected locations, a project under the simulation conditions of this research can achieve a single LEED point from Option 1 only with north-facing windows. As mentioned in the simulation procedure, all the exterior windows are modelled with shades, and whenever more than 2% of the analysis area receives 1000 lux or more of the direct sunlight, the shades are simulated as though they are closed. As a result, no point is achieved in sun-facing spaces, because the roller shade is down during a significant number of the analysis hours.

Table 15. Option 1 sDA$_{300/50\%}$ annual simulation summary for Phoenix

Phoenix (AZ) (5%)				
	sDA(Clear)	**sDA(Shades)**	**sDA(Combined)**	**Point**
South	95.94	0.23	15.27	0
Southwest	96.75	1.6	23.14	0
West	79.62	0	34.14	0
Northwest	54.28	0	43.4	1
North	48.03	0	46.64	1
Northeast	49.65	0	38.88	0
East	65.74	0	25.92	0
Southeast	91.66	0	14.58	0

We see almost similar results for Pittsburgh (Table 16). Since Pittsburgh is mostly cloudy compared to Arizona, shades are down for less time and thus, we see a higher final sDA$_{300/50\%}$, still, no daylighting points are achieved using Option 1 to simulate daylighting in the space.

Table 16. Option 1 sDA$_{300/50\%}$ annual simulation summary for Pittsburgh

Pittsburgh (PA) (5%)				
	sDA(Clear)	**sDA(Shades)**	**sDA(Combined)**	**Point**
South	62.15	0	22.8	0
Southwest	60.18	0	28.58	0
West	51.62	0	34.37	0
Northwest	44.44	0	39.23	0
North	40.04	0	39.81	0
Northeast	42.01	0	38.07	0
East	46.52	0	30.9	0
Southeast	54.16	0	24.65	0

Going to Bismarck, ND, we see the lowest amount of final sDA$_{300/50\%}$ and no LEED point in any orientation due to the site conditions (Table 17).

Table 17. Option 1 sDA$_{300/50\%}$ annual simulation summary Bismarck (ND)

Bismarck (ND) (5%)				
	sDA(Clear)	**sDA(Shades)**	**sDA(Combined)**	**Point**
South	87.38	0	10.64	0
Southwest	75	0	20.94	0
West	53	0	33.21	0
Northwest	40.04	0	36.22	0
North	37.26	0	37	0
Northeast	38.42	0	33.21	0
East	49.74	0	25	0
Southeast	70.83	0	13.88	0

Miami has the second highest annual sunlight hours among the five locations and again no LEED point is achieved in south-facing spaces, while the three north-facing spaces receive one point (Table18). Comparing Phoenix and Miami, we can see that Miami performs better. This happens because Phoenix has more sunny days compared to Miami, and thus more hours with closed shades.

Seattle shows similar results to Bismarck (ND) and no LEED point is achieved in any orientation, even north, due to the dominant overcast sky conditions (Table 19).

Table 18. Option 1 sDA$_{300/50\%}$ annual simulation summary Miami (FL)

Miami (FL) (5%)				
	sDA(Clear)	**sDA(Shades)**	**sDA(Combined)**	**Point**
South	85.53	0	35.53	0
Southwest	86.92	0	37.84	0
West	74.76	0	43.17	1
Northwest	59.49	0	52.19	1
North	54.16	0	53.93	1
Northeast	56.48	0	47.8	1
East	65.39	0	34.49	0
Southeast	78.12	0	20.71	0

Table 19. Option 1 sDA$_{300/50\%}$ annual simulation summary, Seattle (WA)

Seattle (WA) (5%)				
	sDA(Clear)	**sDA(Shades)**	**sDA(Combined)**	**Point**
South	63.65	0	12.03	0
Southwest	59.72	0	21.64	0
West	47.53	0	29.62	0
Northwest	39.58	0	34.50	0
North	35.76	0	35	0
Northeast	35.53	0	32.4	0
East	40.74	0	26.96	0
Southeast	50.92	0	18.05	0

3.2. Results of Option 2

Option 2 shows somewhat reversed results, since LEED v4.1 doesn't apply shading for this Option. As mentioned in the literature review, Option 2 is a point-in-time calculation and analyses are performed at 8:30 A.M. and 2:30 P.M. on the equinox (within 15 days of September 21st and March 21st) for all locations but Phoenix. Simulations for Phoenix were performed at 9:30 a.m. and 3:30 p.m. because Arizona doesn't apply daylight saving time.

As can be seen, Phoenix and Miami achieve more points due to more annual sunshine hours, and higher angle sunlight, compared to other locations. Phoenix receives more points in a south orientation than the other locations. In contrast to Option 1, there is no achieved point in the three north-facing orientations at almost all the locations (the exception is northeast in Miami and Phoenix), since these orientations do not receive much direct sunlight.

Table 20. Option 2 point-in-time simulation summary for Phoenix

Phoenix	Total percentage ≥ 300 and <3000	Points
South	86.66	2
Southwest	59.32	1
West	60.16	1
Northwest	52.58	0
North	35.76	0
Northeast	58.91	1
East	59.11	1
Southeast	69.39	1

Table 21. Option 2 point-in-time simulation summary for Pittsburgh

Pittsburgh	Total percentage ≥ 300 and <3000	Points
South	73.25	1
Southwest	58.30	1
West	60.45	1
Northwest	46.85	0
North	36.75	0
Northeast	54.22	0
East	54.48	0
Southeast	72.81	1

As the tables show, most of the sun-facing orientations achieve points in Option 2, while no point is achieved by spaces with north-facing windows. There is no shade to block the light, and the direct sunlight is permitted to enter into the space. Therefore, projects can achieve more LEED points from Option 2 in a sun-facing space without any type of shading. In contrast, spaces with north-facing windows do not achieve LEED point from Option 2 because of the lack of any direct sunlight and shadowing of the adjacent ground surface.

Table 22. Option 2 point-in-time simulation summary for Bismarck

Bismarck	Total percentage ≥ 300 and <3000	Points
South	59.72	1
Southwest	56.34	1
West	53.70	0
Northwest	30.82	0
North	28.24	0
Northeast	50.29	0
East	37.82	0
Southeast	63.08	1

Table 23. Option 2 point-in-time simulation summary for Miami

Miami	Total percentage ≥ 300 and <3000	Points
South	74.33	1
Southwest	61.49	1
West	62.50	1
Northwest	58.97	1
North	47.61	0
Northeast	63.66	1
East	61.60	1
Southeast	78.94	2

Table 24. Option 2 point-in-time simulation summary for Seattle

Seattle	Total percentage ≥ 300 and <3000	Points
South	63.34	1
Southwest	54.66	0
West	57.38	1
Northwest	43.55	0
North	34.00	0
Northeast	46.12	0
East	55.03	1
Southeast	72.37	1

In the following sections the reasons behind these inconsistent results between Option 1 and Option 2 are considered in more detail.

3.3. Option 1 and Option 2 in comparison of LEED points and daylit area

The previous section has shown the results for Option 1 and Option 2 based on the LEED points achieved under the Daylight Credit. This section will focus on comparing the results based on LEED points, and also the sDA and point-in-time coverage percentages for the daylit area under each Option.

Table 25. Achieved points through Option 1 and Option 2 in five locations and eight orientations

O	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
	Option 1	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**Option 1**	**Option 2**
S	0	2	0	1	0	1	0	1	0	1
SW	0	1	0	1	0	1	0	1	0	0
W	0	1	0	1	0	0	1	1	0	1
NW	1	0	0	0	0	0	1	1	0	0
N	1	0	0	0	0	0	1	0	0	0
NE	0	1	0	0	0	0	1	1	0	0
E	0	1	0	0	0	0	0	1	0	1
SE	0	1	0	1	0	1	0	2	0	1

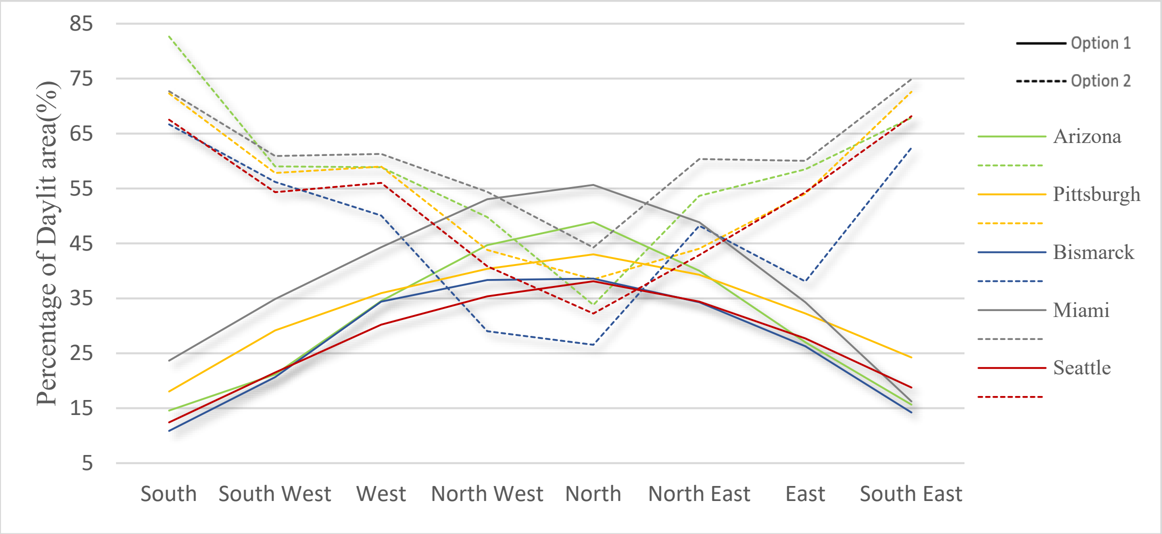
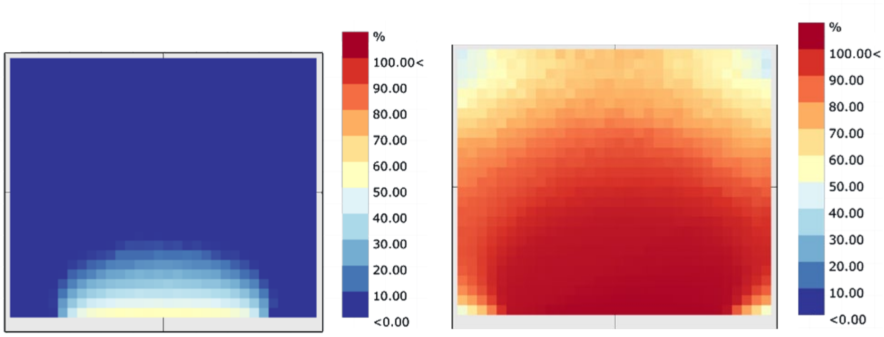


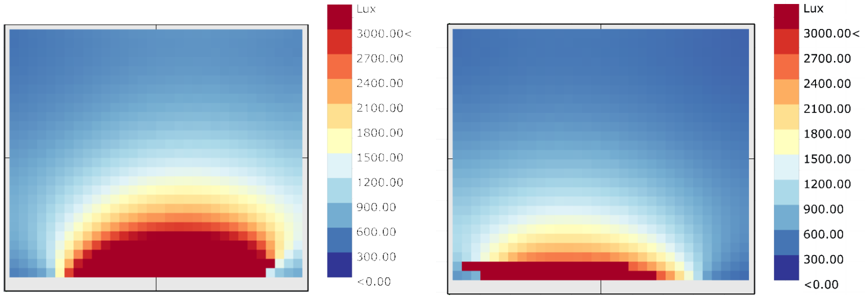
Figure 13. Option 1 vs Option 2 in terms of daylit area percentage

As can be seen in Figure 11 and Table 25, Option 1 and Option 2 results are somewhat reversed. Table 26 shows that south-facing spaces receive points only under Option 2, while the same space with the same windows achieve no points through Option 1. The same happens for north-facing orientations, which achieve points only from Option 1. Considering the daylit area percentage, we can see a similar trend (Figure 3). For example, in a south-facing space where more than 70 percent of the space is daylit under the conditions of Option 2, less than 20 percent is daylit based on Option 1. The same happens in other orientations except for the three north-facing spaces. Figure 3 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.



Option1, **Phoenix**, with shade, Daylight Autonomy, sDA:0.22%

Option 1, **Phoenix**, without shade, Daylight Autonomy, sDA: 95.94%



Option 2, **Phoenix**, Mar 19, 15:30, 90% daylit

Option 2, **Phoenix**, Sep 19, 9:30, 84% daylit

Figure 14. Daylight condition in South-facing space in Phoenix through Option 1 and Option 2

3.4. Detailed analysis of Option 1

In the following sections we look further into Option 1 to consider what factors are contributing to these inconsistent results:

3.4.1. How the roller shade contributes to the results of Option 1

Going more deeply through the results of Option 1, we can see that during a significant portion of the analysis hours the shades are closed. Figure 11 also makes it clear that there is a direct relationship between the sDA value and the number of hours that shades are down. Simulations are performed for a total of 3650 hours (10 hours per day, 8AM to 6PM local time, for a full calendar year of 365 days), and Table 26 shows the number of hours that shades are down in different locations and orientations.

Table 26. The number of hours with down-shades

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

Table 26 reveals that a roller shade has a significant impact on the Option 1 results. We can see that in locations like Phoenix which are mostly sunny during a year, more than half of the total simulation hours (3650) require closed shades. In contrast, the number of hours that shades are down is less in cloudy cities like Pittsburgh and Seattle.

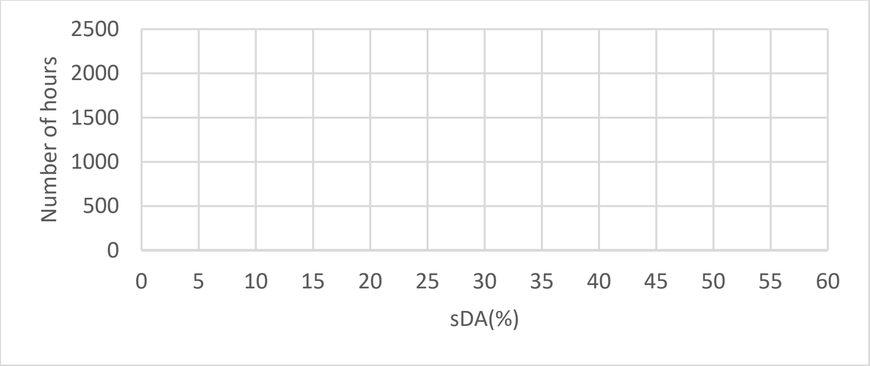


Figure 15. Relation of sDA and the number of hours that shades are down (graph shows all locations and orientations from Table 27)

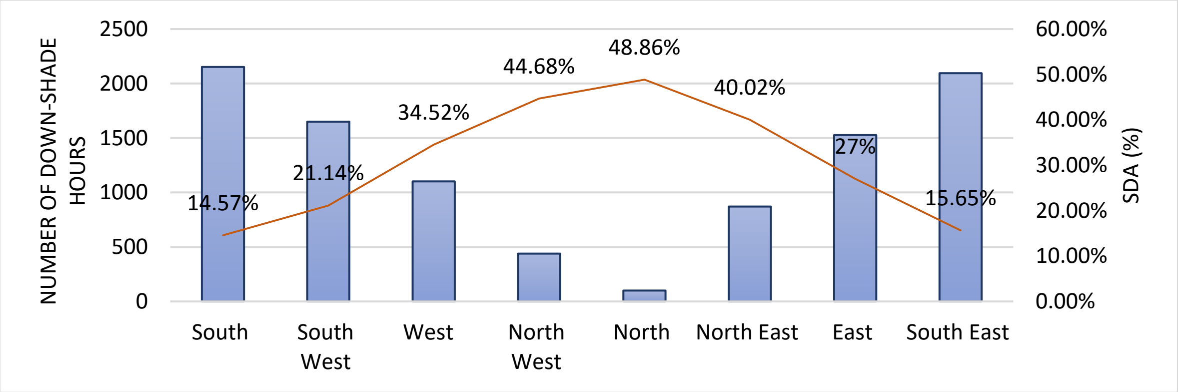


Figure 16. Number of down shade hours in each orientation vs sDA amount in Arizona

Table 27 and Figure 13 also make clear why north-facing spaces are performing better in terms of daylight availability. As can be seen, shades are down less than 100 hours in spaces with northern windows in almost all the locations. Following this, we can see the highest sDA amount in north-facing spaces. There is also a similar trend in spaces with windows facing northwest and northeast.

3.4.2. The impact of roller shade diffuse transmittance

As discussed in previous sections, the roller shade is the main contributor to the inconsistent results of Option 1 and Option 2. As mentioned before, for Option 1 all the exterior windows should be modeled with interior blind/roller shade and whenever more than 2% of the analysis points receive direct sunlight, blinds/roller shade should be lowered. Following this, IES LM-83 recommends using a roller shade with a diffuse transmittance (DT) of 5% when the shade material is unknown. This means that whenever the roller shade is down, most of the direct sunlight is blocked, but if we increase the diffuse transmittance, we should see a significant change in results. The following chart shows how sDA increases when the shading devices DT is changed from 5% to 20%.

As can be seen in Figure 14, there is a significant change in the amount of sDA in sun-facing orientations, while we see no changes in north-facing spaces. As mentioned before, the number of hours that shades are down is less in north-facing spaces, and thus changing diffuse transmittance has less impact on the results for these orientations. We don't see any changes in achieved LEED points of spaces with a Northern window. This means that the low $\text{sDA}_{300/50\%}$

amount is not related to shading device properties and it is due to reduced daylight at these orientations.

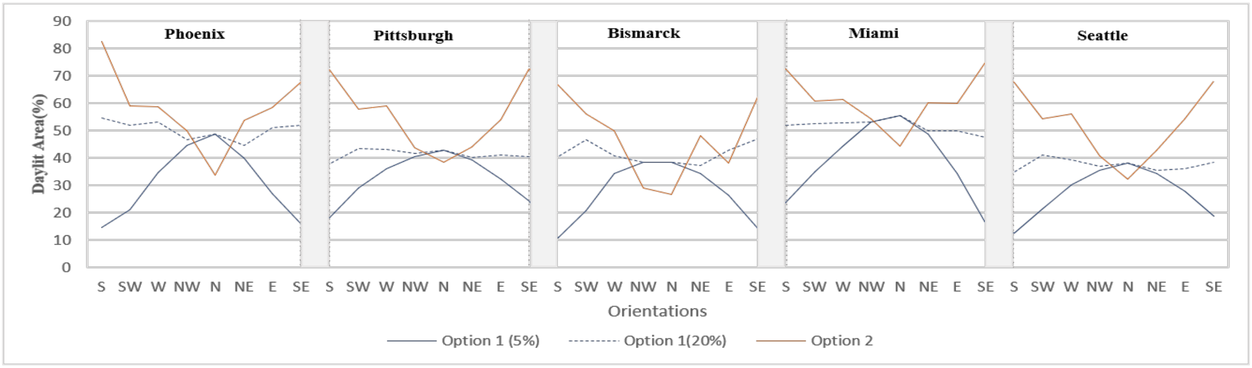
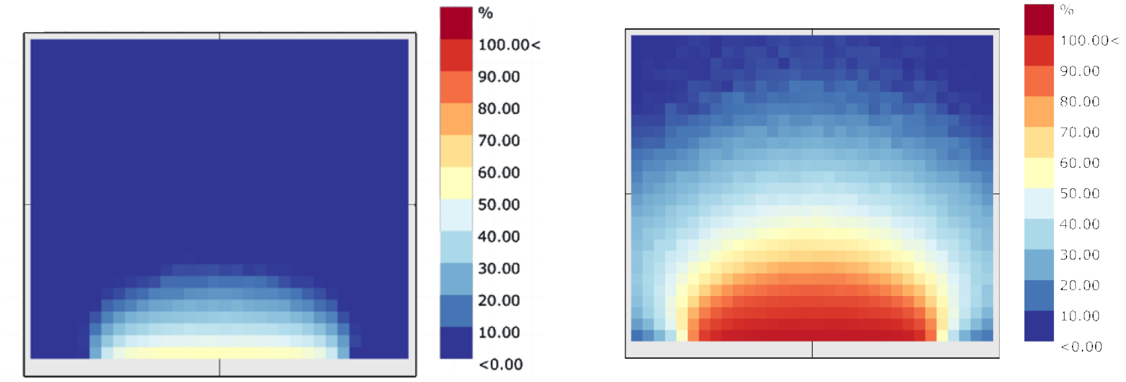


Figure 17. How sDA changes with increasing diffuse transmittance from 5% to 20%

Table 27. Achieved points through Option 1 with 5% and 20% DT

O	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
	Option 1 (5%)	Option 1 (20%)	Option 1 (5%)	Option 1 (20%)	Option 1 (5%)	Option 1 (20%)	Option 1 (5%)	Option 1 (20%)	Option 1 (5%)	Option 1 (20%)
S	0	2	0	1	0	1	0	1	0	0
SW	0	2	0	1	0	1	0	1	0	1
W	0	1	0	1	0	1	1	1	0	0
NW	1	1	0	0	0	0	1	1	0	0
N	1	1	0	0	0	0	1	1	0	0
NE	0	1	0	0	0	0	1	1	0	0
E	0	1	0	0	0	1	0	1	0	0
SE	0	1	0	1	0	1	0	1	0	0

Table 28 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. Overall, increasing DT from 5% to 20% provides more LEED points (through Option 1) in almost all orientations, except the three north-facing ones, at locations with more sunny days (Phoenix, Miami, Bismarck).



Phoenix, with 5% DT roller-shade
South-facing window
sDA:0.22%

Phoenix, with 20% DT roller-shade
South-facing window
sDA:22.1%

Figure 18. How daylight availability changes with increasing diffuse transmittance from 5% to 20%

Table 28. Achieved points through Option 1 and Option 2 with increase of DT from 5% to 20%

O	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2
S	1	2	1	1	1	1	1	1	0	1
SW	1	1	1	1	1	1	1	1	1	0
W	1	1	1	1	1	0	1	1	0	1
NW	1	0	0	0	0	0	1	0	0	0
N	1	0	0	0	0	0	1	0	0	0
NE	1	0	0	0	0	0	1	1	0	0
E	1	1	0	0	1	0	1	1	0	0
SE	1	1	1	1	1	1	1	1	0	1

3.5. Impact of adding an overhang to the results of Option 1 and Option 2

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 28 shows that the LEED daylight points level results change when the overhang is added to the model. It is evident that locations with more sunshine hours (Phoenix, Miami) achieved more LEED points under Option 1 in South and South West orientations. Adding an overhang leads to fewer hours with closed shades, and as a result, more daylight penetrates into the space.

Table 29. Points achieved through Option 1 with and without overhang

Orientation	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
	Points	Points with overhang	Points	Points with overhang	Points	Points with overhang	Points	Points with overhang	Points	Points with overhang
S	0	1	0	0	0	0	0	1	0	0
SW	0	1	0	0	0	0	0	1	0	0
W	0	0	0	0	0	0	1	1	0	0
NW	1	0	0	0	0	0	1	1	0	0
N	1	0	0	0	0	0	1	0	0	0
NE	0	0	0	0	0	0	1	0	0	0
E	0	0	0	0	0	0	0	0	0	0
SE	0	0	0	0	0	0	0	0	0	0

Table 30 and 31 illustrate how adding an overhang contributes to an increase of sDA(%) through a decrease in number of hours that shades are closed.

Table 30. The percentage of daylit area through Option 1 with and without overhang

O	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
	sDA (%)	sDA(%) with overhang	sDA (%)	sDA(%) with overhang	sDA (%)	sDA(%) with overhang	sDA (%)	sDA(%) with overhang	sDA (%)	sDA(%) with overhang
S	15.27	48.84	22.8	26.27	10.64	28.24	35.53	50.57	12.03	23.95
SW	23.14	42.82	28.58	27.31	20.94	27.19	37.84	47.68	21.64	22.45
W	34.14	34.95	34.37	277	33.21	27.54	43.17	40.27	29.62	24.53
NW	43.4	35.18	39.23	28.7	36.22	26.62	52.19	40.74	34.50	25.92
N	46.64	33.1	39.81	28.12	37	26.15	53.93	37.5	35	25
NE	38.88	31.48	38.07	27.89	33.21	25.34	47.8	36.92	32.4	23.72
E	25.92	29.51	30.9	25.92	25	23.03	34.49	33.33	26.96	22.33
SE	14.58	32.63	24.65	25	13.88	18.75	20.71	39.23	18.05	20.37

Table 31. How the number of hours with lowered-shades changes by adding overhang

O	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
	Without overhang	with overhang	Without overhang	with overhang	Without overhang	with overhang	Without overhang	with overhang	Without overhang	with overhang
S	1944	1157	1341	788	2014	1052	1544	797	1605	752
SW	1558	745	1046	547	1336	742	1296	560	1107	641
W	1060	529	652	357	725	380	952	453	637	354
NW	366	31	207	23	161	0	402	59	200	18
N	88	0	17	0	65	0	69	26	0	0
NE	803	479	374	239	528	328	773	443	365	246
E	1519	975	861	547	1163	816	1370	862	832	552
SE	1996	1155	1217	733	1771	1217	1659	874	1305	810

Results for Option 2 show an opposite trend after adding the overhang. As can be seen in Table 31, points are reduced in some orientations. It also displays that by adding an overhang the percentage of daylit area is reduced.

Table 32. Points achieved through Option 2 with and without an overhang

O	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
	Points without overhang	Points with overhang	Points without overhang	Points with overhang	Points without overhang	Points with overhang	Points without overhang	Points with overhang	Points without overhang	Points with overhang
S	2	1	1	1	1	1	1	1	1	1
SW	1	1	1	1	1	1	1	1	0	0
W	1	0	1	0	0	0	1	1	1	1
NW	0	0	0	0	0	0	1	0	0	0
N	0	0	0	0	0	0	0	0	0	0
NE	1	0	0	0	0	0	1	0	0	0
E	1	1	0	0	0	0	1	1	1	1
SE	1	1	1	1	1	1	2	2	1	1

Table 33. The percentage of daylit area through Option 2 with and without an overhang

O	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
	Daylit area (without overhang) (%)	Daylit area (with overhang) (%)	Daylit area (without overhang) (%)	Daylit area (with overhang) (%)	Daylit area (without overhang) (%)	Daylit area (with overhang) (%)	Daylit area (without overhang) (%)	Daylit area (with overhang) (%)	Daylit area (without overhang) (%)	Daylit area (with overhang) (%)
S	86.66	64.76	73.25	72.28	59.72	65.74	74.33	67.80	63.34	57.81
SW	59.32	59.20	58.30	57.33	56.34	55.58	61.49	58.83	54.66	54.20
W	60.16	53.04	60.45	56.77	53.70	42.42	62.50	56.63	57.38	52.58
NW	52.58	44.13	46.85	39.00	30.82	23.26	58.97	47.69	43.55	34.87
N	35.76	26.85	36.75	27.72	28.24	21.64	47.61	34.46	34.00	23.21
NE	58.91	46.99	54.22	44.85	50.29	41.29	63.66	54.46	46.12	35.13
E	59.11	57.75	54.48	51.97	37.82	35.36	61.60	58.16	55.03	35.76
SE	69.39	68.34	72.81	69.88	63.08	58.47	78.94	75.61	72.37	65.80

Figure 15 shows graphically how the Option 1 data are impacted by window direction, while the Option 2 results always decreased with the addition of an overhang.

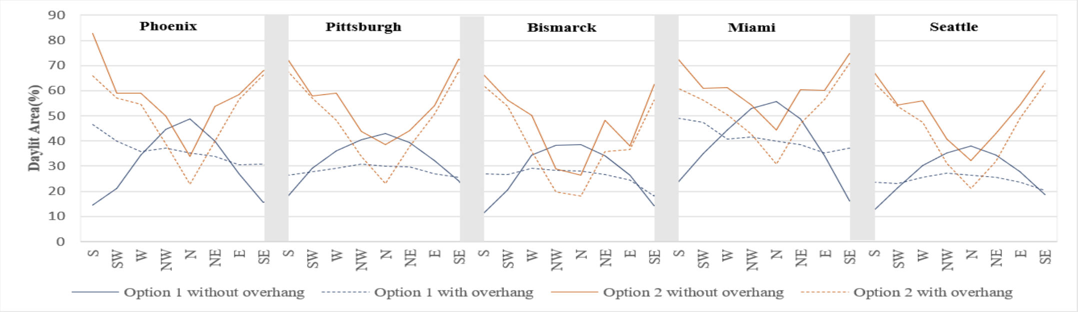
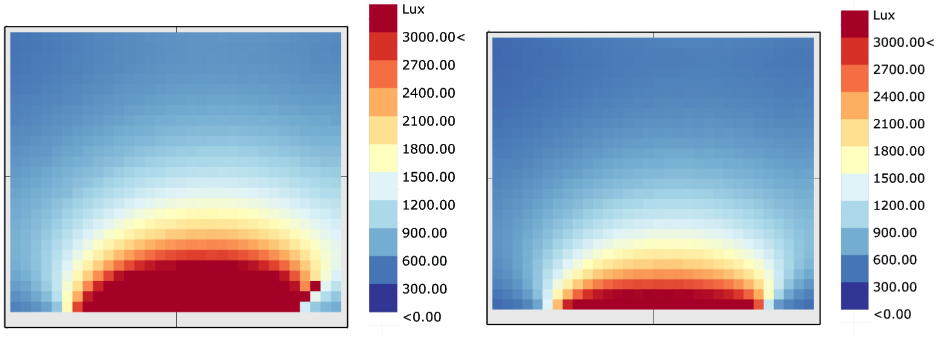


Figure 19. Option 1 vs Option 2 with consideration of overhang



Phoenix, Mar 19, 15:30, without overhang
90% within 300-3000lx

Phoenix, Mar 19, 15:30, with overhang
89% within 300-3000lx

Figure 20. How daylight availability changes with adding an overhang (Option 2)

Table 34 compares LEED points achieved by each option after adding the overhang, and it shows that Option 2 still provides more points in most of the locations.

Table 34. LEED point through Option 1 and Option 2 with overhang

O	Phoenix		Pittsburgh		Bismarck		Miami		Seattle	
	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2
S	1	1	0	1	0	1	1	1	0	1
SW	1	1	0	1	0	1	1	1	0	0
W	0	0	0	0	0	0	1	1	0	1
NW	0	0	0	0	0	0	1	0	0	0
N	0	0	0	0	0	0	0	0	0	0
NE	0	0	0	0	0	0	0	0	0	0
E	0	1	0	0	0	0	0	1	0	1
SE	0	1	0	1	0	1	0	2	0	1

Overall, adding an overhang only contributes to more points through Option 1 in south-facing orientations at locations with more sunny days. For Option 2, additional points are not achieved by adding an overhang, and some point loss can occur (a west orientation in Phoenix is an example).

Summary of findings

Different approaches adopted by the first two simulation options for achieving LEED daylight credits have led to the following results:

- Despite LEED's goal to promote high performance buildings, pursuing daylight credit could result in designs that head in opposite directions in some cases depending on simulation the option that is applied. In other words, a space can achieve more LEED points with no consideration of sustainable daylight strategies like the addition of shading. Even adding an overhang to the window can reduce the achieved points under the conditions of Option 2 in some cases (south orientation in Phoenix, west-facing spaces in Phoenix, Pittsburgh, Seattle, and Miami). As a consequence, architects might conclude that it could be better to neglect sustainable daylighting features in their design.

- In 2012, IES LM-83-12 was created to develop new climate-based metrics to describe multiple important dimensions of daylighting performance. Two metrics, sDA and ASE, are described in IES LM-83-12 for the evaluation of daylight performance of a space over a typical year. LEED Option 1 adopts these two metrics for daylight assessment, but since Option 2 contributes to more LEED points in most cases, and is simpler to apply, Option 1 is not popular among certified projects. This happens because Option 1 blocks direct sunlight through blind/shades whenever more than 2% of the analysis area receives 1000 lux or more. These inconsistent results will lead to the use of older metrics which are less accurate.

- Analyzing the results of Option 1 in detail reveals that the roller shade is the main contributor to sDA(%) amount.

- Another parameter with a significant impact on the results of Option 1 is the diffuse transmittance of the operable window shading devices. The IES LM-83-12 recommends a 5% diffuse transmittance as the default value. This chapter showed how sDA(%) amount can change by increasing the diffuse transmittance from 5% to 20% (Table 27). Increasing the DT of the shade also makes the results of Option 1 and Option 2 more aligned, but in some cases, Option 2 still achieves more points than Option 1 (Phoenix, Pittsburgh, and Seattle for a south-facing window, Table 28).

- If a project seeks to maximize its LEED point Daylight Credits, it needs an investigation based on location, orientation, and shading condition to consider which option contributes to more points.

- USGBC needs to re-examine the Daylight Credit simulation options. In summary, since Option 2 considers no shades and is calculated under the clearest sky condition, an alternative would be to also include shades under different sky conditions. For example, Seattle has more cloudy days than sunny during a year, and when calculations are done with the clearest sky condition, the results cannot be applied to the whole year.

Summary

The findings of this study clearly show that significantly different results are presented by 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.

Chapter 4: Alternative Simulation Conditions

The findings of the last chapter 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. For better agreement between the two approaches, this chapter considers some modifications applied to Option 2.

4.1. Changing the sky conditions in Option 2

As mentioned in chapter 1, for climate modeling, Option 2 uses the TMY weather data of a day within 15 days of September 21 and March 21 that has the clearest sky condition (total sky cover at its lowest value) at 9 A.M an 3 P.M. Total sky cover ranges between 0 and 10, and the lowest value (0) means clear sky. This section considers using different sky condition for Pittsburgh. Figure 16 shows the sky condition for a whole year (working hours) based on total sky cover. As can be seen only 15% of the working hours during a year has the clear sky condition (total sky value 0), and during more than 40% of the year the sky is overcast. Therefore, calculating daylight availability with the clearest sky condition in Pittsburgh (more than 300 cloudy days in 2018), and generalizing it to the whole year seems inaccurate.

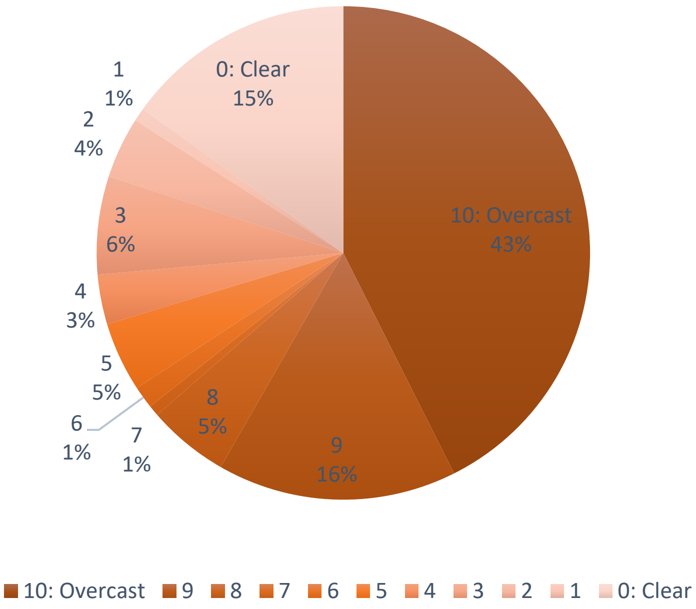


Figure 21. Sky condition in Pittsburgh based on total sky cover

To consider how sky condition affects the daylight availability in a space, simulations were run in Pittsburgh on different days with various sky conditions. Days are selected based on total sky cover and the amount of Direct Normal Radiation (W/m2).

As table 35 and 36 show, changing the sky condition to overcast has a great impact on daylight availability of the studied space in all orientations. It is also clear that there is no LEED point achieved with the new condition. Comparing this with Option 1, we can see that both options perform similar in terms of LEED points.

Table 35. Option 2 point-in-time simulation summary for Pittsburgh with different sky condition

O	TOTAL SKY COVER:9			TOTAL SKY COVER:5			TOTAL SKY COVER:8			TOTAL SKY COVER:10			DAYLIT AREA (%) >=300 AND <=3000	POINTS
	Direct Normal Radiation {Wh/m2}: 47			Direct Normal Radiation {Wh/m2}: 12			Direct Normal Radiation {Wh/m2}: 33			Direct Normal Radiation {Wh/m2}: 12				
	22-Sep, 8:30 a.m.			1-Oct, 2:30 p.m.			28-Mar, 8:30 a.m.			27-Mar, 2:30 p.m.				
	Number of points			Number of points			Number of points			Number of points				
	<300	>=300 and <=3000	>3000	<300	>=300 and <=3000	>3000	<300	>=300 and <=3000	>3000	<300	>=300 and <=3000	>3000		
S	627	237	0	406	408	50	634	230	0	587	277	0	**33.33**	**0**
SW	653	211	0	391	421	52	657	207	0	588	276	0	**32.26**	**0**
W	667	197	0	420	399	45	673	191	0	589	275	0	**30.73**	**0**
NW	665	199	0	469	367	28	670	194	0	593	271	0	**29.83**	**0**
N	650	214	0	497	350	17	653	211	0	596	268	0	**30.18**	**0**
NE	621	243	0	507	341	16	622	242	0	600	264	0	**31.54**	**0**
E	591	273	0	488	359	17	594	270	0	596	268	0	**33.85**	**0**
SE	594	270	0	452	380	32	602	262	0	590	274	0	**34.32**	**0**

Table 36. Results for Pittsburgh through Option 1 and Option 2

O	Pittsburgh					
	Daylit area (%) (Option 2, Clear Sky)	**Points (Option 2, Clear Sky)**	**Daylit area (%) (Option 2, Overcast Sky)** *	**Points (Option 2, Overcast Sky)**	**sDA (%) (Option 1)**	**Points (Option 1)**
S	73.25	1	**33.33**	**0**	22.8	0
SW	58.30	1	**32.26**	**0**	28.58	0
W	60.45	1	**30.73**	**0**	34.37	0
NW	46.85	0	**29.83**	**0**	39.23	0
N	36.75	0	**30.18**	**0**	39.81	0
NE	54.22	0	**31.54**	**0**	38.07	0
E	54.48	0	**33.85**	**0**	30.9	0
SE	72.81	1	**34.32**	**0**	24.65	0

*Simulations are done at 8:30 a.m. on Sep 22 and Mar 28, and at 2:30 p.m. on Oct 1, and Mar 27

Figure 17 compares Option 1 and Option 2 in terms of daylit area (%) with the new sky condition. It can be seen that Option 2 with overcast sky is more aligned with Option 1 in most of directions. It is obvious that further studies are needed to consider locations with various sunlight exposure conditions.

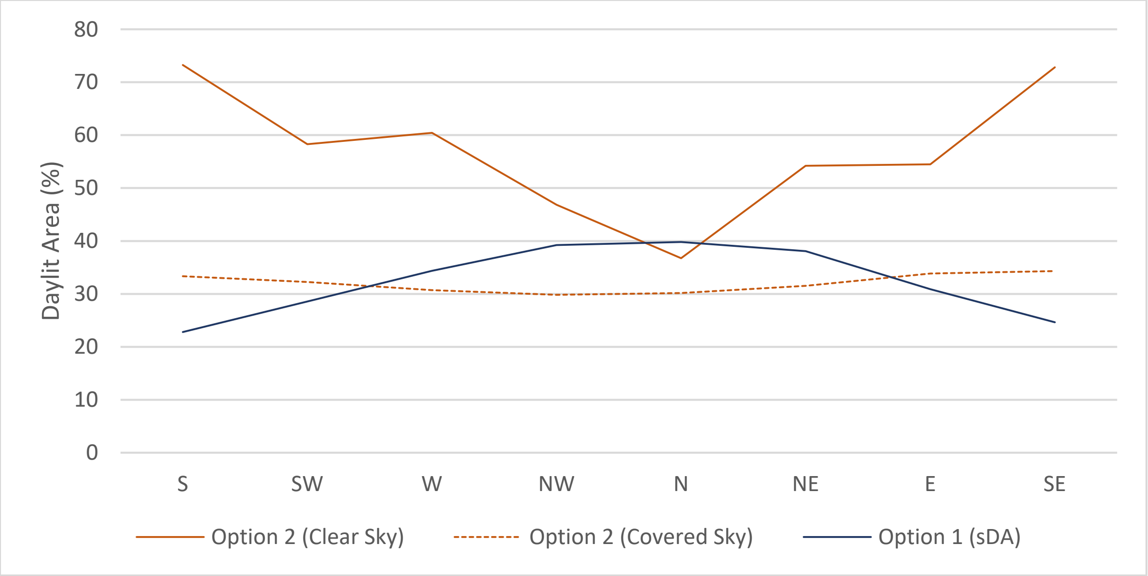


Figure 22. Percentage of daylit area through Option 1 and Option 2

4.2. Adding shades to Option 2

As mentioned in the simulation procedure, in Option 1 all the exterior windows should be modelled with shades, and whenever more than 2% of the analysis area receives 1000 lux or more, the shades should be closed, however, Option 2 considers no application of shades. Chapter 3 shows how shades contribute to the results of Option 1, and we can see that during a significant portion of the analysis hours shades are closed. To consider the performance of Option 2 with shades, the same roller shade used for Option 1 is applied to Option 2 with DT of 5% and 20%.

As the following tables show, adding a roller shade to Option 2 significantly affects the results. There is no LEED point achieved through Option 2 after adding shades. Pittsburgh, Seattle, and Bismarck achieve the same points through Option 1 and Option 2 after adding shades, but Phoenix and Miami still show different results.

Table 37. Results for Phoenix

O	Option 2 (5%)		Option 2 (20%)		Option 2 (no shade)		Option 1(5%)		Option 1(20 %)	
	Daylit area (%)	Points	Daylit area (%)	Points	Daylit area (%)	Points	sDA (%)	Points	sDA (%)	Points
S	4.83	0	31.05	0	86.66	2	15.27	0	58.33	2
SW	10.01	0	45.37	0	59.32	1	23.14	0	56.25	2
W	7.15	0	35.27	0	60.16	1	34.14	0	51.85	1
NW	0.00	0	6.68	0	52.58	0	43.4	1	45.71	1
N	0.00	0	3.50	0	35.76	0	46.64	1	46.64	1
NE	1.85	0	15.36	0	58.91	1	38.88	0	43.05	1
E	11.00	0	47.37	0	59.11	1	25.92	0	49.53	1
SE	11.23	0	49.25	0	69.39	1	14.58	0	51.62	1

Table 38. Results for Pittsburgh

O	Option 2 (5%)		Option 2 (20%)		Option 2 (no shade)		Option 1(5%)		Option 1(20 %)	
	Daylit area (%)	Points	Daylit area (%)	Points	Daylit area (%)	Points	sDA (%)	Points	sDA (%)	Points
S	7.23	0	43.40	0	73.25	1	22.8	0	40.04	1
SW	9.52	0	44.30	0	58.30	1	28.58	0	42.59	1
W	3.88	0	23.03	0	60.45	1	34.37	0	41.31	1
NW	0.00	0	4.72	0	46.85	0	39.23	0	39.46	0
N	0.00	0	3.53	0	36.75	0	39.81	0	39.81	0
NE	2.40	0	18.69	0	54.22	0	38.07	0	39.46	0
E	9.26	0	44.73	0	54.48	0	30.9	0	39.23	0
SE	8.42	0	44.53	0	72.81	1	24.65	0	40.04	1

Table 39. Results for Bismarck

O	Option 2 (5%)		Option 2 (20%)		Option 2 (no shade)		Option 1(5%)		Option 1(20 %)	
	Daylit area (%)	Points	Daylit area (%)	Points	Daylit area (%)	Points	sDA (%)	Points	sDA (%)	Points
S	0.52	0	46.15	0	59.72	1	10.64	0	40.16	1
SW	8.85	0	41.06	0	56.34	1	20.94	0	45.37	1
W	1.53	0	12.96	0	53.70	0	33.21	0	39.69	0
NW	0.00	0	1.68	0	30.82	0	36.22	0	36.68	0
N	0.00	0	1.42	0	28.24	0	37	0	36.68	0
NE	3.15	0	20.20	0	50.29	0	33.21	0	35.64	0
E	9.84	0	45.02	0	37.82	0	25	0	40.5	1
SE	9.06	0	47.54	0	63.08	1	13.88	0	45.83	1

Table 40. Results for Miami

O	Option 2 (5%)		Option 2 (20%)		Option 2 (no shade)		Option 1(5%)		Option 1(20 %)	
	Daylit area (%)	Points	Daylit area (%)	Points	Daylit area (%)	Points	sDA (%)	Points	sDA (%)	Points
S	3.07	0	25.41	0	74.33	1	35.53	0	53.58	1
SW	6.45	0	33.71	0	61.49	1	37.84	0	53.47	1
W	3.67	0	23.55	0	62.50	1	43.17	1	51.96	1
NW	0.00	0	7.75	0	58.97	1	52.19	1	52.54	1
N	0.00	0	5.79	0	47.61	0	53.93	1	53.93	1
NE	3.96	0	26.24	0	63.66	1	47.8	1	48.72	1
E	10.16	0	44.88	0	61.60	1	34.49	0	48.95	1
SE	7.75	0	43.06	0	78.94	2	20.71	0	47.56	1

Table 41. Results for Seattle

O	Option 2 (5%)		Option 2 (20%)		Option 2 (no shade)		Option 1(5%)		Option 1(20 %)	
	Daylit area (%)	Points	Daylit area (%)	Points	Daylit area (%)	Points	sDA (%)	Points	sDA (%)	Points
S	7.58	0	29.72	0	63.34	1	12.03	0	34.72	0
SW	9.61	0	43.82	0	54.66	0	21.64	0	40.27	1
W	4.20	0	24.83	0	57.38	1	29.62	0	38.42	0
NW	0.00	0	5.09	0	43.55	0	34.50	0	35.30	0
N	0.00	0	3.27	0	34.00	0	35	0	35.3	0
NE	0.87	0	15.16	0	46.12	0	32.4	0	33.79	0
E	6.63	0	41.81	0	55.03	1	26.96	0	34.83	0
SE	6.42	0	44.50	0	72.37	1	18.05	0	36.45	0

In terms of the percentage of daylit area, we can see that roller shades with 5% DT block sunlight and Option 2 provides less daylit area compared to Option 1. However, 20% DT provides more aligned results in the three south-facing orientations, but there is still a large discrepancy in the three north-facing orientations.

Chapter 5: Conclusions

The results of a simulation study of a simple room with side-lighting (i.e., windows) show that the two simulation methods currently being applied in LEED (v4.1) to assess Daylight Credits provide significantly different levels of daylight coverage and LEED points for a given window orientation and window shading conditions. The inconsistent results between these two approaches happen due to different calculation conditions. Option 1 fully adopts the Climate-Based Daylight Modelling (CBDM) approach, predicting hourly daylight quantity on an annual basis, including the application of interior shades when direct sunlight enters the space, while Option 2 measures daylight performance on some days and hours, with no consideration of interior shading. 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 the shades must be closed more often to prevent direct sunlight penetration. For better agreement between these two approaches, alternative modifications to the simplified approach were examined. Although, applying interior window shading device with higher transmittance (20%) makes the results more aligned, further investigation is still needed to consider how often during the year these devices must be applied. The simplified approach must also incorporate various sky conditions, given that it currently uses the clearest sky condition for all locations. An approach that combines at least one clear sky, one overcast sky, and assesses interior daylight conditions with blinds/shades applied, along with an evaluation of site weather conditions, would appear necessary to improve the alignment of a more simplified approach with the full sDA analysis of LEED's Option 1.

A simplified approach that is better aligned with the sDA approach should be possible with further study.

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