The Pennsylvania State University

The Graduate School

College of Engineering

THE IMPACT OF OVERHANG LENGTH, WINDOW ORIENTATION, AND CLIMATE ON SPATIAL DAYLIGHT AUTONOMY (SDA) AND ANNUAL SUNLIGHT EXPOSURE (ASE) FOR A CLASSROOM

A Thesis in

Architectural Engineering

by

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Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

August 2016
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ABSTRACT

Daylighting has advantages in energy savings when integrated with electric lighting, and it has visual discomfort issues like electric lighting as well. To better deploy daylighting, IES LM-83-12 proposed two metrics: Spatial Daylight Autonomy (sDA\textsubscript{300/50%}) and Annual Sunlight Exposure (ASE\textsubscript{1000, 250h}) to evaluate the daylight conditions in a space. sDA\textsubscript{300/50%} indicates the sufficiency of daylight inside a room and the ASE\textsubscript{1000, 250h} shows the potential risks of visual discomfort. The LEED V4 criteria introduced the application of spatial daylight autonomy and annual sunlight exposure for the evaluation of daylight credits.

In order to have a better perspective on sDA and ASE, conventional metrics such as Daylight Factor (DF), Daylight Autonomy (DA), Useful Daylight Illuminance (UDI) and continuous Daylight Autonomy (cDA) were reviewed and compared with the two new metrics. This research was designed to investigate the sDA\textsubscript{300/50%} and the ASE\textsubscript{1000, 250h} of a classroom with dimensions of 33 feet × 30 feet × 10 feet excluding furniture and partitions. 6 selected cities were grouped by 3 latitudes. 8 façade orientations were applied in 45° steps. Overhang lengths ranging from 0 feet (non-overhang) to 4 feet (with a 5 feet overhang added to the ASE\textsubscript{1000, 250h} simulations), shading devices like roller shades and blinds, and climate (indicated by the sunshine hours) were included in this research as variables. The non-GUI advanced version of DAYSIMps and other program scripts were implemented in the simulations. ASE\textsubscript{1000, 250h} does not account for shading devices so there is no difference between roller shades and blind conditions for this metric. sDA\textsubscript{300/50%} was studied for the roller shades with 5% VLT and horizontal blinds were modeled in two different approaches (a translucent material with 20% VLT distribution and real geometry with 80% reflectance) per IES LM-83.

The simulation results of ASE\textsubscript{1000, 250h}, are dependent on the solar angles determined by the latitudes, window orientations, and the overhang length. The climate also affects the ASE results because of the sunshine hours throughout a year. The sDA denotes mainly the diffuse light penetration inside a space. The sDA\textsubscript{300/50%} results are impacted by the shading on/off hours and the climate. The shading devices were lowered if the direct sunlight covered more than 2% of the work plane area. The shading options are impacted by the window orientations, overhang lengths, and climate.

Recommendations were provided to help designers improve the daylight performance inside the classroom. The directions of north, northeast, and northwest are the preferred orientations for achieving low ASE values. The longer overhang helps to increase the sDA in south, southwest, southeast, west and east facing and lowers the ASE only slightly on these orientations, but it still high. Adjustments to the overhang or aperture sizes can be made according to the climate to achieve better daylight performance and budget savings. As expected, the blinds have better sDA\textsubscript{300/50%} than the 5% VLT roller shades due to their higher transmittance.
Further studies to comprehensively evaluate daylight conditions and energy savings in total building energy are encouraged.
TABLE OF CONTENTS

LIST OF FIGURES ........................................................................................................... vii
LIST OF TABLES .............................................................................................................. ix
ACKNOWLEDGEMENTS .................................................................................................. xii

Chapter 1  INTRODUCTION ............................................................................................ 1
  1.1 Daylighting: Energy versus Comfort .................................................................... 1
  1.2 LEED V4 Daylight credits .................................................................................... 2
  1.3 Scope ..................................................................................................................... 2
  1.4 Research hypothesis ............................................................................................ 3

Chapter 2  LITERATURE REVIEW .................................................................................. 4
  2.1 Daylight basics ...................................................................................................... 4
    2.1.1 Daylight angles and site locations ................................................................. 4
    2.1.2 Sky conditions and climate ......................................................................... 6
    2.1.3 Overhang and interior shading devices ......................................................... 8
  2.2 Daylight metrics .................................................................................................... 8
    2.2.1 Daylight Factor (DF) .................................................................................... 9
    2.2.2 Daylight Autonomy (DA) ............................................................................. 9
    2.2.3 Useful Daylight Illuminance (UDI) ............................................................... 9
    2.2.4 Continuous Daylight Autonomy (cDA) ......................................................... 10
    2.2.5 Spatial Daylight Autonomy (sDA) ................................................................. 10
  2.3 sDA and ASE Simulation ...................................................................................... 11
    2.3.1 Building 3D Modeling for sDA and ASE ...................................................... 11
    2.3.2 Climate modeling for sDA and ASE .............................................................. 12
    2.3.3 DAYSIMps .................................................................................................... 13

Chapter 3  METHODOLOGY ............................................................................................ 15
  3.1 Simulation Setup .................................................................................................... 15
    3.1.1 Sites and locations ...................................................................................... 15
    3.1.2 Model configuration .................................................................................... 15
    3.1.3 DAYSIMps settings .................................................................................... 18
  3.2 Data processing ..................................................................................................... 20
    3.2.1 Annual Sunlight Exposure (ASE) ................................................................. 20
    3.2.2 Spatial Daylight Autonomy (sDA) for roller shades with 5% VLT ............... 21
    3.2.3 Spatial Daylight Autonomy (sDA) for blinds ............................................... 21

Chapter 4  RESULTS AND DISCUSSION ....................................................................... 23
  4.1 Analysis of ASE_{1000, 250h} .............................................................................. 23
4.1.1 Simulation results ................................................................. 23
4.1.2 Discussion ........................................................................... 25
4.2 Analysis of sDA$^{300/50\%}$ with different shading devices .............. 28
  4.2.1 Simulation results of sDA$^{300/50\%}$ for roller shades with 5% VLT .... 28
  4.2.2 Simulation results of sDA$^{300/50\%}$ for blinds with 20% VLT ........ 30
  4.2.3 Simulation results of sDA$^{300/50\%}$ for blinds in real geometry with 80% reflectance ................................. 32
  4.2.4 Discussion ........................................................................... 34
4.3 Recommendations for improving the daylight performance in a classroom ................................................. 37

Chapter 5 Conclusions ........................................................................ 39
  5.1 Daylight conditions in a classroom space with an overhang: A perspective ........................................... 39
  5.2 Limitations and future work ........................................................................................................... 40

BIBLIOGRAPHY .................................................................................... 42

Appendix A: Supplemental tables and figures .................................................. 46
  A.1 Minimum solar profile angles between 8 AM to 6 PM for each city ........ 46
  A.2 Blind rotation angles in 12 months for each city ........................................ 48
  A.3 Annual hours of profile angles below the cut-off angles of overhang for each city ........................ 50
  A.4 Annual hours of shades down in the analysis period for each city .................. 52

Appendix B: Important subroutines used in the simulation .......................... 53
  B.1 Minimum solar profile angles calculation between 8 AM to 6 PM for each city (VBA) .... 53
    B.1.1 Func_CalcAp ........................................................................ 53
    B.1.2 Func_CalcAs ........................................................................ 53
    B.1.3 Func_CalcAt ........................................................................ 53
    B.1.4 Func_CalcSoT ...................................................................... 53
    B.1.5 Main_min_profileangle .......................................................... 53
  B.2 Annual hours of profile angles are below the cut-off angles for each city (VBA) ........ 56
  B.3 Python scripts for extracting monthly data and new .ill data combination with sDA$^{300/50\%}$ calculation ........................................ 62
  B.4 The matrix plot of the shade options in the analysis period all year round (Matlab script) ...... 64
LIST OF FIGURES

Figure 2-1 The variation of solar azimuth angle and altitude angle with latitude [2]..................................................5
Figure 2-2 Solar position determined by $a_a$ (solar azimuth angle) and $a_t$ (solar altitude angle) and their relationship with $a_p$ (solar profile angle) [2] ..........................................................................................................................6
Figure 2-3 Solar Profile Angle frequencies by latitude and elevation azimuth angle [2]..............................6
Figure 2-4 The Annual Mean Sunshine Hours across the United States lower 48 states for the years of 1961-1990 [22]..................................................................................................................................................7
Figure 2-5 The modules used in the new DAYSIMps and the function process [51] ..............................14
Figure 3-1 Six cities selected for research on the sunshine hours map (adapted from [22]) and their locations ..................................................................................................................................................15
Figure 3-2 The dimensions (ft. length) of the classroom model (top) used in this research with the left view (bottom left) and front view (bottom right) .................................................................16
Figure 3-3 Model check by rendering Images .........................................................................................16
Figure 3-4 The illustration of the calculation points distribution in the classroom .........................20
Figure 4-1 Variations of ASE$_{1000, \ 250h}$ of different window orientations, climate, and overhang lengths around 33°N..................................................................................................................................................24
Figure 4-2 Variations of ASE$_{1000, \ 250h}$ of different window orientations, climate, and overhang lengths around 40°N..................................................................................................................................................24
Figure 4-3 Variations of ASE$_{1000, \ 250h}$ of different window orientations, climate, and overhang lengths around 47°N..................................................................................................................................................24
Figure 4-4 The cut-off angle illustration of the 5 ft overhang considering to the first row of analysis points ..................................................................................................................................................25
Figure 4-5 Solar path at 40°N, red dotted lines are the analysis period in summer time, adapted from [2]26
Figure 4-6 Variations of sDA$_{300/50\%}$ for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 33°N..................................................................................................................................................29
Figure 4-7 Variations of sDA$_{300/50\%}$ for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 40°N..................................................................................................................................................29
Figure 4-8 Variations of $sDA_{300/50\%}$ for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 47°N.......................................................... 29

Figure 4-9 Variations of $sDA_{300/50\%}$ for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 33°N.......................................................... 31

Figure 4-10 Variations of $sDA_{300/50\%}$ for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 40°N.......................................................... 31

Figure 4-11 Variations of $sDA_{300/50\%}$ for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 47°N.......................................................... 31

Figure 4-12 Variations of $sDA_{300/50\%}$ for blinds with 80% reflectance of different window orientations, climate, and overhang lengths around 33°N.......................................................... 33

Figure 4-13 Variations of $sDA_{300/50\%}$ for blinds with 80% reflectance of different window orientations, climate, and overhang lengths around 40°N.......................................................... 33

Figure 4-14 Variations of $sDA_{300/50\%}$ for blinds with 80% reflectance of different window orientations, climate, and overhang lengths around 47°N.......................................................... 33

Figure 4-15 Shade operation at south facing changing from 0 ft overhang to 4 ft overhang over 3650 hours. The light color bars show that the shades are down and the dark color bars means shades are up ............ 36

Figure A-1 Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length changing with orientations for the cities around 33°N ........................................... 51

Figure A-2 Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length changing with orientations for the cities around 40°N ........................................... 51

Figure A-3 Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length changing with orientations for the cities around 47°N ........................................... 51

Figure A-4 Variations in number of hours shades are down in the analysis period throughout a year in cities around 33°N ............................................................................................................. 52

Figure A-5 Variations in number of hours shades are down in the analysis period throughout a year in cities around 40°N ............................................................................................................. 52

Figure A-6 Variations in number of hours shades are down in the analysis period throughout a year in cities around 47°N ............................................................................................................. 52
LIST OF TABLES

Table 1-1 Points for daylit floor area: Spatial Daylight Autonomy [7] ......................................................... 2
Table 2-1 sDA and ASE comparison ............................................................................................................. 12
Table 3-1 Parameters of the optical properties .......................................................................................... 17
Table 4-1 ASE_{1000, 250h} of different window orientations, climate, and overhang lengths around 33°N  .... 23
Table 4-2 ASE_{1000, 250h} of different window orientations, climate, and overhang lengths around 40°N  .... 23
Table 4-3 ASE_{1000, 250h} of different window orientations, climate, and overhang lengths around 47°N  .... 23
Table 4-4 The cut-off angle of each overhang length to the first row of analysis points in this research  .... 25
Table 4-5 sDA_{300/50%} for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 33°N ............................................................................................... 28
Table 4-6 sDA_{300/50%} for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 40°N ............................................................................................... 28
Table 4-7 sDA_{300/50%} for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 47°N ............................................................................................... 28
Table 4-8 sDA_{300/50%} for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 33°N ............................................................................................... 30
Table 4-9 sDA_{300/50%} for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 40°N ............................................................................................... 30
Table 4-10 sDA_{300/50%} for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 47°N ............................................................................................... 30
Table 4-11 sDA_{300/50%} for blinds with 80% reflectance of different window orientations, climate, and overhang lengths around 33°N ............................................................................................... 32
Table 4-12 sDA_{300/50%} for blinds with 80% reflectance of different window orientations, climate, and overhang lengths around 40°N ............................................................................................... 32
Table 4-13 sDA_{300/50%} for blinds 80% reflectance of different window orientations, climate, and overhang lengths around 47°N ............................................................................................... 32
Table 4-14 Number of hours shades are down in the analysis period throughout a year in cities around 33°N ........................................................................................................................................ 35
Table 4-15 Number of hours shades are down in the analysis period throughout a year in cities around 40°N ..................................................................................................................35

Table 4-16 Number of hours shades are down in the analysis period throughout a year in cities around 47°N ..................................................................................................................35

Table 4-17 Annual sunlight hours of each city based on calculation.........................................................37

Table A-1 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Phoenix ..............................................................................................................46

Table A-2 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Birmingham ..............................................................................................................46

Table A-3 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Denver ..............................................................................................................46

Table A-4 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Pittsburgh ............................................................................................................47

Table A-5 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Fargo ..............................................................................................................47

Table A-6 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Seattle ..............................................................................................................47

Table A-7 The cut-off angle of 0° to 60° blind rotation and the maximum overhang length for sDA calculation .................................................................................................................................48

Table A-8 The rotation angle selected in each month with different window facing orientation in Phoenix .................................................................................................................................48

Table A-9 The rotation angle selected in each month with different window facing orientation in Birmingham ...............................................................................................................................48

Table A-10 The rotation angle selected in each month with different window facing orientation in Denver ..............................................................................................................................48

Table A-11 The rotation angle selected in each month with different window facing orientation in Pittsburgh ..........................................................................................................................49

Table A-12 The rotation angle selected in each month with different window facing orientation in Fargo ..............................................................................................................................49
Table A-13 The rotation angle selected in each month with different window facing orientation in Seattle
...........................................................................................................................................49

Table A-14 Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length for the cities around 33°N........................................................................................................50

Table A-15 Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length for the cities around 40°N........................................................................................................50

Table A-16 Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length for the cities around 47°N........................................................................................................50
ACKNOWLEDGEMENTS

First and foremost, I would like to express my special thanks to my thesis advisor Dr. Richard Mistrick, for his generous help and continuous encouragement in finishing this thesis. I am deeply impressed by his professionalism and devotion on daylight study and consider him as a model of how to do research as a career. Inspired by him, I set up my mind to learn what I am interested in and started electrical engineering as a concurrent degree. Serving as my advisor, Dr. Mistrick fully understood and assisted me in dealing with the sophisticated paper work at the time I applied for the concurrent degrees and this I will never forget.

Dr. Kevin Houser, who taught me the courses on luminaires and color science, is a professor with prudence. I benefited a lot not only from his courses but from his rigorous attitude toward writing with beautiful figures and proper formats as well. Dr. Houser also gave me helpful advice when I told him my decision to continue the concurrent master study and helped me so much when he was the graduate program officer.

Dr. Stephen Treado, I really appreciate your advice and insights in my thesis writing and oral presentation. I also want to extend my sincere gratitude to Dr. Noel Chris Giebink, my advisor in Electrical Engineering, who gave me the opportunity to study in electrical engineering and gave me great help. I am grateful to the other department faculty and staff: Dr. James Freihaut, Dr. Chimay Anumba, Deborah Sam, Corey Wilkinson, and Susan Shutt. Corey, I place on record my special thanks to you for your support in the computer lab and Y drive space, which facilitated me in running simulations efficiently for my thesis.

My AE colleagues and friends, especially the graduate students in the lighting option: Ling Chen, Sarith Subramaniam, Minchen Wei, offered me great assistance in the coursework and the thesis. I am thankful to all of you and will forever cherish our friendship over these years. My time in AE was enjoyable with all of my friends.

Junjie Wang, my roommate in Fudan University, supported me on Python programing in dealing with the illuminance data which cannot be handled by DAYSIMps or Excel VBA. Thanks to his help, the data processing part became much easier and time saving.

My families are also important during my research. My parents, serving as my solid backup force, was always there, supporting me, understanding me and loving me. Rui Sun, my wife, is the best companion in my study and life. Junyi Liu, my cousin, helped me a lot with AutoCAD illustrations. They are the people I treasure and love most throughout my life.

I always think that people need to learn how to be grateful, no matter how trivial the assistance other people give you or help you with. At last, I would like to sincerely appreciate all the people helped me directly or indirectly during these years.
Chapter 1 INTRODUCTION

1.1 Daylighting: Energy versus Comfort

According to the Buildings Energy Data Book published by the US Department of Energy [1], the building sector accounted for about 41% of the primary energy consumption of the United States. Lighting, representing about 16.7% of electric energy consumption of the commercial building, is the largest contributor. Energy shortages, as well as climate change, have become great challenges for humankind. Reduction in carbon emissions needs to be considered and is achieved through green building design.

Daylighting, which utilizes the light from the sun and the sky in a building, is playing a more and more important role in building design. The decrease of lighting energy consumption can be achieved by integrating daylight and electric light together. With better daylighting design in a building, occupants can have a better visual experience and their productivity, as well as their satisfaction, can be improved [2]. In a classroom space, Heschong Mahone Group [3] reported that daylighting introduction can improve student scores 7%-18%.

From an energy savings point of view, by properly utilizing daylighting, the energy consumption of lighting can be reduced. The building itself, however, is a complex system. The energy saved from daylighting may be compromised by losses from other systems, such as the HVAC system [2, 4]. With proper selection of the materials for the building envelope and appropriate aperture sizes, and by applying correct daylight delivery systems, daylighting design integrated with HVAC system performance can achieve optimum energy savings.

The positive effects of daylighting on human circadian rhythms cannot be replicated with electric lighting. Yet, similar to electric light, it has the issue of visual comfort (i.e. glare and visual contrast). To overcome the discomfort issue from daylight, direct sunlight needs to be controlled to a proper level, by means of installing shading devices like roller shades, blinds, fins, light shelves and so on [2]. Shading devices may sacrifice the penetration depth of daylight into a room, but it prevents visual discomfort from direct light from the sun.

A balance of lighting energy savings and visual comfort should be taken into account during the design. As for lighting energy savings, maximizing the illuminance level from daylight will help to bring down energy consumption on electric lighting, but this process may bring unexpected visual discomfort. The benefits of daylighting are promising if daylight is properly addressed. The daylighting design of a building requires an integrated process, such as proper utilization of glazing materials, aperture sizes, and shading systems in accordance with the HVAC system, such that the maximum energy savings and least visual discomfort can be achieved.
Many codes, rating systems, and standards, such as ANSI/ASHRAE/IES Standard 90.1-2013, ANSI/ASHRAE/IES Standard 189.1-2014, LEED V4, IES LM-83-12 [5-9] are dedicated to addressing the current issues and to maximizing the benefits of daylight utilization in buildings.

1.2 LEED V4 Daylight credits

In June of 2013, the U.S. Green Building Council (USGBC) approved the new LEED V4 rating system. The V4 system and LEED 2009 system were both valid until June 1st, 2015, and from then on the LEED V4 became the exclusive LEED rating system. In this new system, the biggest change in the daylight credits was the introduction of Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). The introduction of these two metrics is expected to better characterize the quality of daylighting in buildings.

Spatial Daylight autonomy (sDA), e.g. sDA300/50%, is the percentage of occupied area that achieves 300 lux for 50% of the analysis hours during the year in a project. The caveat, however, involves controlling Annual Sunlight Exposure (ASE), e.g. ASE1000, 250h, which is the percentage of the area in regularly occupied spaces that exceeds 1000 lux from direct sunlight alone more than 250 analysis hours during one year. The new rating system requires this value to be no more than 10% to achieve the daylight credit when sDA targets are achieved. Occupancy hours are typically considered between 8 AM and 6 PM [10]. The LEED V4 daylight credits allotted based on sDA are shown in Table 1-1.

Table 1-1 Points for daylit floor area: Spatial Daylight Autonomy [7]

<table>
<thead>
<tr>
<th>New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses &amp; Distribution Centers, CI, Hospitality</th>
<th>Healthcare</th>
</tr>
</thead>
<tbody>
<tr>
<td>sDA (for regularly occupied floor area)</td>
<td>Points</td>
</tr>
<tr>
<td>55%</td>
<td>2</td>
</tr>
<tr>
<td>75%</td>
<td>3</td>
</tr>
</tbody>
</table>

The simulation of sDA and ASE is limited to calculation grids of no more than 2-foot spacing at a work plane height of 30 inches. Typical meteorological year (TMY) or equivalent data is used for hourly analysis.

The LEED V4 rating system not only considers the adequate daylight levels achieved in the occupied space, but also provides for the limitation of direct sunlight illuminance, which reinforces the visual comfort of the occupants and provides for enhanced views of the exterior if interior shading devices are not required.

1.3 Scope

The study considered here investigates performance in a regularly occupied classroom space with 0 to 4 feet of overhang lengths, involving 8 window orientations in 6 U.S. cities of different climate zones covering a latitude range of 33° to 48°. It characterized the daylight level of the classroom space quantitatively and qualitatively by sDA and ASE through the simulation results of DAYSIMps [11]. This study focused on daylighting conditions and provides recommendations of site orientations and overhang
lengths of similar spaces for architects and designers to achieve higher LEED V4 points. The study has not integrated daylighting with electric lighting control, nor has it addressed the energy consumption of the classroom.

1.4 Research hypothesis

The research hypotheses considered here are that overhang lengths, window orientation and climate have different impacts on the sDA and the ASE of the classroom. An overhang will help to reduce the ASE based on its cut-off angle which is comparable to the solar profile angle. The implementation of these overhangs will alter the number of hours that shades must be lowered and impact the sDA of the classroom space.

An additional hypothesis that will be addressed includes the presumption that it is difficult to achieve the daylight credits in LEED V4. Finally, this study will test the the assumption that 20% VLT, as per IES LM-83, is a good simplified simulation procedure for real blinds with 80% reflectance.
Chapter 2 LITERATURE REVIEW

2.1 Daylight basics

2.1.1 Daylight angles and site locations

To better evaluate daylighting inside a room, one essential step is to understand the relationship of the solar path with regard to the analysis area. The site location (i.e. longitude, latitude) coupled with the time and date, determine the solar time as follows [2]:

\[ t_s = t_{local} - 1 \]  \hspace{1cm} (1)

\[ ET = 0.1644 \sin \left( \frac{4\pi(J-81.6)}{365.25} \right) - 0.1273 \left( \frac{2\pi(J-2.5)}{365.25} \right) \]  \hspace{1cm} (2)

\[ t = t_s - ET + \frac{12(SM-L)}{180} \]  \hspace{1cm} (3)

Where:

- \( t \) = Solar time in decimal hours
- \( t_s \) = Standard time in decimal hours
- \( t_{local} \) = Local time in decimal hours
- \( ET \) = Equation of Time correction for the difference of the earth’s tilt angle in its orbit about the sun
- \( SM \) = Standard meridian for the time zone in degrees.
- \( L \) = Site longitude in degrees

With the above data, the solar position can be located and characterized by two angles, the solar attitude angle and the solar azimuth angle. These two angles are calculated as shown below:

\[ \delta = 0.4093 \sin \left( \frac{2\pi(J-81)}{368} \right) \]  \hspace{1cm} (4)

\[ a_t = \arcsin \left( \sin l \sin \delta - \cos l \cos \delta \cos \left( \frac{at}{12} \right) \right) \]  \hspace{1cm} (5)

\[ a_s = \arctan \left[ \frac{-\cos \delta \sin \left( \frac{at}{12} \right)}{\cos l \sin \delta + \sin l \cos \delta \cos \left( \frac{at}{12} \right)} \right] \]  \hspace{1cm} (6)

Where:

- \( \delta \) = Solar declination in radians
- \( J \) = Julian date (1-365)
- \( a_t \) = Solar altitude in radians
- \( a_s \) = Solar azimuth angle in radians
\( a_s = \text{Solar azimuth angle in radians} \)

\( l = \text{Site latitude in radians} \)

\( t = \text{Solar time in decimal hours} \)

As this study covers locations with latitude from 33° to 47°, Figure 2-1 shows the variation of the two solar angles at two latitudes (40° N and 45°N) within this range.

![Figure 2-1 The variation of solar azimuth angle and altitude angle with latitude [2]](image)

This study investigated the classroom space with 8 orientations (S/SE/E/NE/N/NW/W/SW) and takes into account an overhang and interior shading devices. The profile angle \( a_p \), is another important angle for selecting the overhang lengths and the blind rotation angle. The word ‘profile’, means the solar angle with respect to a vertical plane perpendicular to the facade, and this angle can be derived based on the solar altitude angle, solar azimuth angle, and the facade orientation (characterized by the elevation azimuth angle \( a_e \)). A reference direction is typically selected for both the solar azimuth angle and elevation azimuth angle. The equations provided above reference these angles from south. The calculation of the solar profile angle is as below:

\[
\begin{align*}
a_z &= a_s - a_e \\
a_p &= \arctan\left(\frac{\tan a_s}{\cos a_z}\right)
\end{align*}
\]

Where:

\( a_z = \text{Solar elevation azimuth in radians} \)

\( a_s = \text{Solar azimuth in radians} \)

\( a_e = \text{Elevation azimuth in radians} \)
\[ a_p = \text{Profile angle in radians} \]

Their relationship is shown as Figure 2-2.

**Figure 2-2** Solar position determined by \( a_s \) (solar azimuth angle) and \( a_t \) (solar altitude angle) and their relationship with \( a_p \) (solar profile angle) [2]

The distribution of solar profile angles between 7 AM and 7 PM across the 0° to 180° elevation azimuth angle range for a similar latitude range of this study is shown as Figure 2-3.

**Figure 2-3** Solar Profile Angle frequencies by latitude and elevation azimuth angle [2]

At appropriate profile angles, shading devices and overhangs are implemented to block the direct sunlight.

### 2.1.2 Sky conditions and climate

Daylight contains a contribution not only from the sun, but also a contribution from the sky. Thus, in a deep room without direct sunlight penetration, there is still illuminance from daylight, or even the reflected light from the ground or any other objects [2, 12]. The sky model is an essential part of a daylighting simulation.

The CIE developed a sky model which defines 16 sky types, representing a range of skies from heavily overcast to a cloudless clear sky by the luminance patterns, which are determined by a set of parameters.
and equations [13, 14]. A more accurate sky model, the Perez sky model (luminous efficacy model) [15, 16] is widely used in the simulation of sky conditions given site weather data, which is available for locations all over the world. The Perez luminous distribution model is based on measured solar and global insolation data [17]. It derives sky brightness and sky clearness from the measured diffuse horizontal and direct normal irradiance values for specific locations and dates/times. With these data, the solar and directional sky luminance can be calculated by the Perez model[18]. Diffuse Horizontal Irradiance is the radiation component from the sky alone, measured horizontally. Direct Normal Irradiance is the radiation component from the sun, measured by an irradiance meter aimed directly at the sun. These two groups of data can be extracted from the Energy Plus Weather (EPW) file [19] or the Typical Meteorological Year (TMY) data sets [20].

Different climates result in different sunshine hours. In the United States, the solar sunshine varies dramatically [21], thus the daylight conditions of different places may have notable differences in places with a similar latitude. Figure 2-4 shows the variation of the annual sunlight hours in the lower 48 states of the United States, based on the historical data of 1961-1990 [22]. It was used to characterize the selection of the analysis sites of this study to evaluate sites at similar latitudes which have different sunlight hours.

![Figure 2-4 The Annual Mean Sunshine Hours across the United States lower 48 states for the years of 1961-1990](image)
2.1.3 Overhang and interior shading devices

An overhang, considered as a ‘passive roof’ [23], provides for the obstruction of direct sunlight. It is applied to help block the sunlight beyond a particular profile angle. The overhang improves the occupant’s visual comfort by reducing the introduction of direct sunlight into a space. Research [24-26] also shows that the implementation of an overhang has a potential to reduce the cooling energy load.

Roller shades are traditionally used to control daylight glare and the solar heat gain [27, 28]. Roller shades also provide occupant privacy. The implementation of roller shades is likely to impact lighting energy as well as the cooling or heating load. Shades have the potential for optimizing the total energy consumption through integration with an automatic control system [29-31]. From a daylight control perspective, the important related parameters are the openness factor and the transmittance. The openness factor is the straight on viewing of holes in the material, which may be called specular transmittance. The diffuse transmittance due to the shade material is usually estimated as the total transmittance of the roller shades minus the openness factor [2]. There are other important factors determining the thermal properties, such as thermal transmission (U-factor) and solar heat gain coefficient (SHGC), which will impact the thermal energy analysis [31].

The shades, acting in a Lambertian manner [2], can diffuse the interior light upon transmission. The luminance provided by shades are determined by incident light and shade material.

Horizontal slatted blinds, another typical type of shading device, offer the opportunity for the occupants to adjust the illuminance level by rotating the slats. Daylight from certain angles can penetrate into the room though the spaces between the slats without much attenuation [2]. The blinds provide not only glare control, but permit transmission to accommodate different daylight conditions. Blinds or shades are useful even for the north-facing windows as they have the potential to mediate intolerable glare conditions, such as intermittent specular reflections from glass on adjacent buildings, or on summer days near sunset or sunrise [10].

In Section 2.3.1, the detailed shading device operation of the roller shades and blinds in this study will be discussed.

2.2 Daylight metrics

A variety of daylight metrics have been applied over the years to evaluate the daylight performance in a space.
2.2.1 Daylight Factor (DF)

The Daylight Factor (DF), is defined as the ratio of the internal illuminance at a point in a building to the unshaded, external horizontal illuminance under a CIE overcast sky [32]. This metric was widely accepted and used for many years [33]. The DF can be affected by design aspects like the building aperture size, the surroundings, glazing materials, and the surface reflectances, etc. The DF was meant to evaluate the worst sky condition (an overcast sky) and did not take into account movable shading devices. This made the metric more intuitive and easier for designers to calculate and communicate. However, these restrictions limit its usefulness. C. F. Reinhart et al [34] proposed an extreme condition of ‘the daylight factor optimized building which has a fully glazed building envelope’. This condition, where the DF is very high, seems to be good, as DF characterizes the worst sky condition. In fact, however, this kind of design is a disaster for the occupants. How will they deal with the discomfort glare from direct sunlight? And what about the heating and cooling load inside the building? The answers are evident.

Apart from the flaws mentioned above, the DF only includes the contribution of an overcast sky based on the CIE standard sky model, which is symmetric across all orientations [35]. Other sky conditions like a partly cloudy sky, or even a clear sky, cannot be evaluated by DF. The orientation of a window, which results in different daylighting performance, also cannot be assessed with DF.

2.2.2 Daylight Autonomy (DA)

Daylight Autonomy (DA), is a metric that for one point represents the percentage of occupied time in a year that daylight illuminance exceeds a specific threshold [34, 36]. For example DA\(_{300}\) means the percentage of occupied hours greater than or equal to 300 lux. DA is useful for individual analysis points and measures the daylight hours when there is chance to implement a photosensor to control the electric light. This concept should take into consideration movable binds and roller shades [34].

2.2.3 Useful Daylight Illuminance (UDI)

Useful daylight illuminance (UDI) is defined as the percentage of hours that illuminance falls within the range 100~3000 lux [37]. The range used to define the limits of useful daylight illuminance is based on a comprehensive review of the latest data from field studies of occupant behavior under daylit conditions [38, 39]. The UDI is applied by determining the occurrence of daylight illuminance that:

1. Are within the range defined as useful (i.e. 100~3000 lux);
2. Are Insufficient (i.e. less than 100 lux);
3. Exceed the useful range (i.e. greater than 3000 lux) [37], and therefore may cause discomfort and glare. [40]
Both UDI and DA consider the percentage of occupied hours at a point for which the target illuminance range or illuminance value is met. This percentage is an accumulated value for DA. Yet this cannot show exactly where the illuminance falls in the range for UDI, and is unable to show the partial contribution of within a time span [35].

2.2.4 Continuous Daylight Autonomy (cDA)

Continuous Daylight Autonomy (cDA) is an upgraded version of DA, which includes partial contributions from the daylight hours [41, 42]. It has high correlation with a control system that dims the electric lighting. In the IES Lighting Handbook [2], an example of cDA is provided. If the target illuminance level is set to 500 lux, and during one hour, the space only receives 300 lux of daylight illuminance, the partial contribution, and the credit for that hour, is 300/500 = 0.6. The introduction of cDA makes the compliance with target illuminance more flexible, as partial credit (the non-compliance part) is taken into account [34].

2.2.5 Spatial Daylight Autonomy (sDA)

The Illuminating Engineering Society (IES) reviewed and assessed the above metrics [10], and found that it was not enough for any single metric to include all factors when characterizing the daylight condition of a space, both temporally and spatially. In IES LM-83-12 [10], two metrics were introduced and discussed, which the LEED V4 credits (Section 1.2) apply, Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE). When the two values are reported together, the sufficiency of daylight and the opportunity for excessive direct sunlight penetration are well evaluated.

The definition of sDA and ASE have already been discussed in Section 1.2. When performing the simulation for sDA, the blinds or shades need to be operated hourly to block direct sunlight [10]. The daylight conditions are given by the TMY data.

Very similar to the points in LEED V4, different values of sDA\textsubscript{300/50\%} are identified as acceptable by the IES. An sDA\textsubscript{300/50\%} of 75\%, which corresponds to 3 points of credit in LEED V4 New Construction, Core and Shell, Schools, Retail, Data Centers, Warehouses & Distribution Centers, CI, and Hospitality, is assessed as Preferred Daylight Sufficiency, while 55\% is labeled as the Normally Accepted Daylight Sufficiency [10]. LEED V4 has higher sDA requirement for healthcare facilities, sDA\textsubscript{300/50\%} must be greater than or equal to 90\%, to get the highest points (2 pts) [7].

The modeling of sDA will be discussed in Section 2.3.
2.2.6 Annual Sunlight Exposure (ASE)

The threshold ASE in IES LM-83-12 is the same as that in LEED V4. The ASE should be reported together with sDA for the analysis. The performance criteria under the supporting research done by IES has the following judgments [10]:

1. Unsatisfactory visual comfort when the ASE$_{1000, 250h}$ is more than 10%;
2. Neutral (normally acceptable) when the ASE$_{1000, 250h}$ is less than 7%;
3. Clearly acceptable when the ASE$_{1000, 250h}$ is less than 3%.

IES proposed that the supporting research needed more field research across a variety of solar penetration patterns with variable orientations, space types, shading device types, and climate zones to fully understand the occupants’ preferences [10]. The interpretation of the ASE values were not fully investigated as ASE should be considered as relative values, and a study of larger areas is needed [10].

2.3 sDA and ASE Simulation

2.3.1 Building 3D Modeling for sDA and ASE

The geometry of the space should first be accurately modeled, including the exterior obstructions, the exterior envelope with appropriate materials, and shading devices like overhangs, shades, blinds and so on. The interior surfaces in the space need to be modeled by either measured data, or the IES LM-83-12 recommended values. The period of analysis should be 10 hours per day, from 8 AM to 6 PM local clock time, taking into consideration daylight savings time and the longitude adjustments [10]. The sDA and ASE simulations need to implement TMY weather data. These data, although formatted hourly, are centered on the half-hour. Take the hour 9 for instance, it is 8:30 AM for the TMY weather data, and it’s the average value of the weather data from 8 AM to 9 AM, but the considered solar position should be at 8:30 AM [20].

The supporting research of the metric was conducted through the latitude range from 37° to 48°. The metric may be applicable beyond this range, yet with some uncertainty [43].

The analysis area in a space requires a calculation grid that covers the entire space. The spacing of the grid points should be less than or equal to 2 feet and the offset to the wall should be controlled within 1 to 2 feet [10].

IES LM-83-12 also regulates that the exterior windows must be modeled with blinds/shades unless 1) eliminated by design documents; or 2) The ASE meets or exceeds the recommended criteria for ‘normally acceptable’. The blinds/shades should cover the entire window whenever more than 2% of the analysis points receive direct sunlight (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). The rotation angle of blinds and the position of the shades should be set to block the direct sunlight from the lowest solar angle experienced for the façade orientation in that calendar month at that location, based on the nearest TMY weather file for the 10 hour period [10]. In the modeling for ASE simulation, the shades or blinds should be left open, and only overhangs or other fixed shading devices should be kept in the model.

The Bidirectional Transmittance or reflectance Scattering Function (BSDF) data of non-specular material [44-46] is critical for routine implementation of complex fenestration systems. These data provide a more accurate simulation by defining the specular and diffuse contribution of the blind/shade material. IES LM-83-12 also suggests that without BSDF data, the shades can be modeled by the Visible Light Transmission (VLT), which combines the specular and diffuse transmittance. The specular transmittance can be approximated to the openness factor given by the manufacturer, and the diffuse transmittance can be approximated the by the subtraction of openness factor from the VLT [47]. If the shade material is unknown, a 5% diffuse VLT should be applied to assess the performance of roller shades.

When the BSDF data is not available for the blinds, some estimate should be made for the blinds. For example, for blinds with 80% or higher reflectance, IES LM-83 states that a 20% VLT diffuse transmittance should be applied for both sunlight and skylight. The VLT of darker colored blinds should be reduced proportionally to 10% VLT at a blind reflectance of 0% [10]. Table 2-1 provides a comparison of sDA and ASE.

### Table 2-1 sDA and ASE comparison

<table>
<thead>
<tr>
<th></th>
<th>sDA</th>
<th>ASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of analysis</td>
<td>10 hours per day (8AM to 6PM)</td>
<td></td>
</tr>
<tr>
<td>Illuminance threshold</td>
<td>300 lux</td>
<td>1000 lux</td>
</tr>
<tr>
<td>Temporal threshold</td>
<td>1825 hours per year</td>
<td>250 hours per year</td>
</tr>
<tr>
<td>Analysis Area</td>
<td>Regularly occupied work areas</td>
<td></td>
</tr>
<tr>
<td>Analysis Points</td>
<td>No greater than 2’ by 2’ spacing, 1’ to 2’ offset from the walls, at 30” in height</td>
<td></td>
</tr>
<tr>
<td>Blinds/Shades Operation</td>
<td>Close whenever more than 2% of the analysis points receive direct sunlight</td>
<td>No deployment</td>
</tr>
<tr>
<td>Blinds/Shades optical properties</td>
<td>1. BSDF data; 2. BSDF unavailable: shades use 5% diffuse VLT; Blinds with 80% reflectance use 20% VLT. Both shades and blinds block the direct sunlight from the lowest angle in a calendar month</td>
<td>&quot;Zero bounce&quot; of other reflectance surfaces (ab=0)</td>
</tr>
</tbody>
</table>

2.3.2 **Climate modeling for sDA and ASE**

The climate modeling is based on the hourly TMY weather data, and this data will be applied through the Perez sky model (discussed in Section 2.1.2) to get the luminance contribution from the sun and the sky.
The concept of daylight coefficients, first proposed by Tregenza and Waters [48], is to theoretically divide the celestial hemisphere into disjoint sky patches, and to calculate the contribution of each sky patch to the total illuminance inside a room. Bourgeois and Reinhart [18] developed a standard daylight coefficient model for Dynamic Daylighting Simulations (DDS), and this model contains the contribution from different luminous sources for dynamic daylighting simulations:

1. 145 diffuse sky segments
2. 1 diffuse ground segment
3. 145 indirect solar positions
4. 2305 direct solar positions

This DDS model defines the illuminance data that is independent of the analysis space location or orientation, and provides an efficient and accurate method for computer based daylight calculations. It provides functionality to independently take into account controlled daylighting sources (e.g. windows and skylights) and to query different daylighting quantities in a simulation context [18]. The modeling for ASE does not consider the contribution from the sky, nor the contribution from other reflected surfaces (zero bounce aforementioned). When running the simulations, the modelers are recommended to apply high parameter settings to yield more reliable results [10].

2.3.3 DAYSIMps

The sDA and ASE simulations in this study were performed using the DAYSIMps Software modified by the Penn State University [11]. DAYSIM is a RADIANCE-based simulation software that implements the daylight coefficients [49] and the Perez Sky Model [50]. New functions and modules are developed and added into DAYSIM [11, 51], making it have the capability to calculate sDA under shades and blinds (with fixed rotation angles), and the ASE for the analysis space. Since the current version is non-GUI based, to achieve the simulation results, the following steps are required:

1. Create header file with system description, file links, requested output, and processing parameters;
2. Run DAYSIMps executable modules referencing the header file (See Figure 2-5 for the modules and processing flow chart);
3. Output files contain calculation results.

In this research, three essential modules were used in order to get the simulation results: gen_dc_adv.exe, sDA.exe, and aSunExp.exe.
Figure 2-5 The modules used in the new DAYSIMps and the function process [51]

The settings for the header file as well as the parameters for simulation will be introduced and discussed in Chapter 3. The results of the simulations will be summarized in Chapter 4.
Chapter 3 METHODOLOGY

3.1 Simulation Setup

3.1.1 Sites and locations

Six cities were selected as indicated in Figure 3-1. They are arrayed in pairs with similar latitude but with very different sunshine conditions, and cover the latitude range 37° to 48° [10] used in the supporting research for IES LM 83-12.

![Map of six cities](image)

Figure 3-1 Six cities selected for research on the sunshine hours map (adapted from [22]) and their locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seattle, WA</td>
<td>47.45°</td>
<td>122.30°</td>
</tr>
<tr>
<td>Fargo, ND</td>
<td>46.90°</td>
<td>96.80°</td>
</tr>
<tr>
<td>Pittsburgh, PA</td>
<td>40.50°</td>
<td>80.22°</td>
</tr>
<tr>
<td>Denver, CO</td>
<td>39.76°</td>
<td>104.86°</td>
</tr>
<tr>
<td>Birmingham, AL</td>
<td>33.57°</td>
<td>86.75°</td>
</tr>
<tr>
<td>Phoenix, AZ</td>
<td>33.43°</td>
<td>112.02°</td>
</tr>
</tbody>
</table>

The cities selected represent different annual sunshine hours according to the map. Simulations of the classroom space with different shading devices and overhang lengths in each city were conducted with 8 orientations (S/SE/E/NE/N/NW/W/SW) separated by 45°, making it possible to investigate the impacts of overhang length and window orientation on the sDA and ASE. The locations of the sites and the daylight conditions are provided in the weather files.

3.1.2 Model configuration

In this study, the classroom is located on the first floor of the building. The model was rotated into the 8 different orientations (S/SW/SE/W/E/N/NW/NE). The 3D module was setup through AutoCAD, and each surface was defined by a 3D face in AutoCAD. The model was then converted into rad files that are readable by DAYSIM. The dimensions of the model are shown as Figure 3-2. Note that Figure 6 shows the model with an overhang length of 4 ft. In the simulation conducted for this research, the overhang length was changing from 0 ft (no overhang) to 5 ft length in 1 foot steps. The Window-to-Wall Ratio (WWR) is about 41%.
The dimensions (ft. length) of the classroom model (top) used in this research with the left view (bottom left) and front view (bottom right).

In DAYSIM, the model was extended with extra polygons accounting for the exterior wall and outside ground of the classroom. The model was then verified and checked using the genimage.exe module from RADIANCE. The rendered images are shown in Figure 3-3.
The exterior wall is 1 foot thick and the window glass is at the center. The shades and blinds were installed 0.5 feet inside the window to cover the whole window and block the direct sunlight. The horizontal blinds were created using the genblinds.exe module in RADIANCE (the polygons of the slats were created). The optical properties assigned to the windows with shades/blinds [10], and to all the reflecting surfaces, are listed in Table 3-1.

Table 3-1 Parameters of the optical properties

<table>
<thead>
<tr>
<th>Surfaces</th>
<th>Materials</th>
<th>Reflectance</th>
<th>80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling</td>
<td>Reflectance</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>Wall</td>
<td>Reflectance</td>
<td>60%</td>
<td></td>
</tr>
<tr>
<td>Floor</td>
<td>Reflectance</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Overhang</td>
<td>Reflectance</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>Exterior wall</td>
<td>Reflectance</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td>Ground</td>
<td>Reflectance</td>
<td>10%</td>
<td></td>
</tr>
</tbody>
</table>

Window parameters

| WWR               | 41% |
| Glazing Transmittance | 65% |
| Sill Reflectance   | 50% |

Roller shades parameters

| Visible Light Transmission (VLT) | 5% |
| Openness factor                 | 0% |
| Diffuse Transmittance           | 5% |
| Solar Reflectance               | 50% |

Horizontal blind parameters

| Visible Light Transmission (VLT) | 20% |
| Slat reflectance                 | 80% |
| Rotation angles                  | 0° to 60°, in 15° step |
| Slat depth                       | 1" |
| Slat spacing                     | 0.9" |
| Total number of slats            | 67 |

The roller shade modeling is simple, applying a translucent material with 5% VLT to a polygon that covers the window. The modeling for blinds in this thesis, is considered using two approaches without a BSDF: The first approach uses a 20% VLT diffuse distribution for blinds treated as a rectangle of translucent material that covers the entire window. The diffuse reflectance is estimated as 22%, which was computed for a blind rotation angle of 15°. The second approach uses an 80% reflectance for each blind slat, and the blinds are built in real geometry with a plastic, diffuse Radiance material. The blind rotation angle is configured to block the lowest sunlight angle during the analysis period within each month.
3.1.3 DAYSIMps settings

The geometry of the model (without shading devices) was converted to Radiance files using the module of dxf2rad in RADIANCE. The optical properties of the model were recorded in the material rad files based on the layer name in the geometric rad files. Unlike the model characterized by 2 separate files: geometric rad file and material rad file, the rad file for a shading device is just one file, including both geometric and material information. Take the roller shades for example, the shades rad file is in the form shown below:

```plaintext
void trans 1_shade    # 5% VLT
0
0
7 .55 .55 .55 0 0 .091 0
1_shade polygon 1_shade.1.1
0
0
12 3 1 8
30 1 8
30 1 3
3 1 3
```

The upper part indicates the optical properties and the second section contains the geometric information. For the shade rad file, both material and geometry were included in one file while for the model without the shading device, they were written in two separate files.

The material settings for blind modeling Approach 1 and Approach 2 are shown respectively below:

```plaintext
void trans 1_blinds    # 20% VLT with 22% reflectance
0
0
7 .42 .42 .42 0 0 .476 0
void plastic white    # 80% reflectance with real geometry
0
0
5 .8 .8 .8 0 0
```

To link all the information together, a header file was created containing all the paths of the essential files and the parameters for simulation. An example (Seattle, when the window facing south, 0° S) of the header file for the non-GUI based DAYSIMps is in the below form, with the parameters in DAYSIMps set to high values for more accurate sDA calculations [10]. The Ambient Bounces (ab) was set to 0 for ASE calculation.

```plaintext
project_name S0_adv
project_directory c:/S0/
bin_directory c:/daysim/bin/
tmp_directory tmp/
material_directory c:/daysim/
ies_directory c:/daysim/
```

```
#######
# site information
#######
place SEATTLE USA
```
latitude 47.45
longitude 122.30
time_zone 120
site_elevation 122.0
ground_reflectance 0.2
wea_data_file C:\sample\USA_WA_Seattle-Tacoma.727930_TMY2_60min.wea
wea_data_file_units 1
first_weekday 1
time_step 60
wea_data_short_file wea/USA_WA_Seattle-Tacoma.727930_TMY2_60min.wea
wea_data_short_file_units 1
lower_direct_threshold 2
lower_diffuse_threshold 2
output_units 2

#########################################################################
# building information
#########################################################################
material_file rad/classroom_mat.rad
geometry_file rad/classroom.rad
rotationNumber 1
rotate_z 0.0
sensor_file pts/1.pts

shading -11
WG_1 1
automated_signal PS1 16.5 0 3 0 -1 0 0 3000

matl_case 1 rad/empty.rad 1 l_window 1
rad/shades_full.rad

photosensor_control 1
PS1 1 pts/cos.sen

input_unit_index 3
output_unit_index 0
display_unit_index 3
occupancy_profile occ/8to18.csv
DaylightGlareProbability_ViewPoints no_DGP_view_file_provided
DC_file_format Daysim_original

sDA_settings 300 .50 8 18

target_illuminance 500

#########################################################################
# RADIANCE parameters
#########################################################################
ab 7
ad 1500
as 100
ar 300
aa 0.1
lr 6
st 0.1500
sj 1.0000
lw 0.004000
dj 0.0000
ds 0.200
dr 2
dp 512
After the model was set up and the header file was created, the following steps were completed before starting the simulation:

1. The rad files of the model, as well as the shading device containing the geometric and material information, were copied to the \rad folder;
2. The weather file (.wea file converted from EPW file) was imported into the \wea folder;
3. The occupancy file (.occ file) indicating the analysis period from 8 AM to 6 PM was copied to the \occ folder;
4. The calculation points file (.pts file) including the position of the analysis grids and the sensor file (.sen file) were transferred to the \pts folder, and the grids for this study were created following the requirement of IES LM-83-12, as Figure 3-4 demonstrates;

After these preparations, the gen_dc_adv module was executed on the header file, and the illuminance data were achieved. With the illuminance data, data processing could then be performed.

3.2 Data processing

3.2.1 Annual Sunlight Exposure (ASE)

The ASE results were calculated directly from the aSunExp module. As aforementioned, ASE is the same for both roller shades and blind conditions since the ASE calculation does not account for the shading
devices. The overhang was considered in the calculation based on IES-83-12. ‘Zero bounces’ were deployed by setting \( ab=0 \). The calculation result is in the file ending with ASE.res under the \( \text{res} \) folder.

3.2.2 Spatial Daylight Autonomy (sDA) for roller shades with 5% VLT

The sDA calculation of the classroom with 5% VLT roller shades is also pretty straightforward, which can be achieved directly through the sDA module. The sDA calculation takes account of the shading devices which control the direct sunlight shining into the room when direct sunlight exceeds 2% of the analysis points. As high parameter settings were implemented in DAYSIMps, accurate results were obtained in the file with suffix ‘sda’ under the \( \text{res} \) folder.

3.2.3 Spatial Daylight Autonomy (sDA) for blinds

The sDA calculation for the classroom with 20% VLT blinds is similar to that of the roller shades. The sDA calculation for 80% reflectance blind slats with real geometry, however, cannot be calculated directly through the current sDA module in DAYSIMps, as IES LM-83-12 requires “the rotation angle of the blinds and the position of the shades should be set to block the direct sunlight from the lowest solar angle experienced for the façade orientation in that calendar month at that location, based on the nearest TMY weather file for the 10 hours period” [10]. The current DAYSIMps for this research cannot take into consideration blind rotation angles that vary month by month.

Although the sDA calculation under different blind conditions cannot be done directly, the good news is that DAYSIMps can provide the illuminance data for all the analysis points throughout the year as long as a fixed blind rotation angle was input to the blinds rad file. To deal with the sDA calculation for the blinds in the classroom with one specific window orientation and overhang length (other orientations and overhang lengths conditions can be achieved in the same manner), the extended steps below were performed in this research:

1. Run the gen_dc_adv.exe module to get the illuminance data (.ill files) for the blind rotation angles changing from 0° to 60° one by one, in 15° intervals. Thus 5 individual .ill files were obtained in this step.
2. Calculate the blind rotation angle (selected from 0°, 15°, 30°, 45°, and 60°) that can block the lowest solar angle from direct sunlight for the model in each month, e.g. in January a 60° blind rotation angle blocks the lowest solar angle in that month. By such analogy, the lowest blind angles for each month were calculated. By accomplishing this step, 12 blind rotation angles were calculated and mapped to the 12 months in a year. The lowest solar angles for each city and each condition can be found in Appendix A.1, and the blind rotation angles for each city with different orientations and overhang lengths are shown in Appendix A.2.
3. The illuminance data from January to December were extracted month by month from the 5 .ill files obtained from the first step, according to the monthly rotation angles of the 12 months achieved in the second step.
4. Combine the extracted monthly data with different blind rotation angles to a new .ill file for the whole year period.
5. Calculate the sDA\textsubscript{300/50%} of the analysis area from the final .ill and the occupancy period.

Step 1 was finished directly using the modules of DAYSIMps. Note that under the current version DAYSIMps, several .ill files were created through one run, and the ill file ending with adv_dds was the desired one for the next steps since it accounted for the on and off effect of the blinds. The blind rotation angles that were used to block the direct sunlight in Step 2 were calculated through an Excel spread sheet and VBA subroutines by integrating the sunlight angles and site locations discussed in Section 2.1.1. Step 3 to Step 5 were accomplished by a Python subroutine since the data formats and structures are the same for the 6 cities with 8 orientations and 5 overhang lengths. The VBA subroutines and the Python scripts are attached in Appendix B.
Chapter 4 RESULTS AND DISCUSSION

4.1 Analysis of $\text{ASE}_{1000, 250h}$

4.1.1 Simulation results

The $\text{ASE}_{1000, 250h}$ simulation results of the 6 cities with 6 overhang lengths facing 8 orientations are recorded in Table 4-1, 4-2, and 4-3. The values are formatted by color scale with deeper red indicating a higher ASE. To make it more intuitive, the variations of $\text{ASE}_{1000, 250h}$ across the 6 cities and window orientations are demonstrated in Figure 4-1, 4-2, and 4-3. Initially, only the overhang conditions with length ranging from 0 ft (no overhang) to 4 ft were simulated. A 5 ft overhang was added to the simulation, to show how longer overhang length impacts the ASE in the classroom space, which will be discussed in Section 4.1.2.

Table 4-1 $\text{ASE}_{1000, 250h}$ of different window orientations, climate, and overhang lengths around 33°N

<table>
<thead>
<tr>
<th>City (33°N)</th>
<th>Phoenix, AZ (more daylight hours)</th>
<th>Birmingham, AL (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>$\text{ASE}_{1000, 250h}$</td>
<td>$\text{ASE}_{1000, 250h}$</td>
</tr>
<tr>
<td>Overhang Length (ft.)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Orientation</td>
<td>0° (S)</td>
<td>25.0%</td>
</tr>
<tr>
<td></td>
<td>45° (SE)</td>
<td>37.1%</td>
</tr>
<tr>
<td></td>
<td>90° (E)</td>
<td>41.1%</td>
</tr>
<tr>
<td></td>
<td>135° (NE)</td>
<td>20.1%</td>
</tr>
<tr>
<td></td>
<td>180° (N)</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>225° (NW)</td>
<td>25.0%</td>
</tr>
<tr>
<td></td>
<td>270° (W)</td>
<td>42.4%</td>
</tr>
<tr>
<td></td>
<td>315° (SW)</td>
<td>35.7%</td>
</tr>
</tbody>
</table>

Table 4-2 $\text{ASE}_{1000, 250h}$ of different window orientations, climate, and overhang lengths around 40°N

<table>
<thead>
<tr>
<th>City (40°N)</th>
<th>Denver, CO (more daylight hours)</th>
<th>Pittsburgh, PA (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>$\text{ASE}_{1000, 250h}$</td>
<td>$\text{ASE}_{1000, 250h}$</td>
</tr>
<tr>
<td>Overhang Length (ft.)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Orientation</td>
<td>0° (S)</td>
<td>33.9%</td>
</tr>
<tr>
<td></td>
<td>45° (SE)</td>
<td>39.3%</td>
</tr>
<tr>
<td></td>
<td>90° (E)</td>
<td>36.0%</td>
</tr>
<tr>
<td></td>
<td>135° (NE)</td>
<td>15.2%</td>
</tr>
<tr>
<td></td>
<td>180° (N)</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>225° (NW)</td>
<td>16.1%</td>
</tr>
<tr>
<td></td>
<td>270° (W)</td>
<td>34.8%</td>
</tr>
<tr>
<td></td>
<td>315° (SW)</td>
<td>34.4%</td>
</tr>
</tbody>
</table>

Table 4-3 $\text{ASE}_{1000, 250h}$ of different window orientations, climate, and overhang lengths around 47°N

<table>
<thead>
<tr>
<th>City (47°N)</th>
<th>Fargo, ND (more daylight hours)</th>
<th>Seattle, WA (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>$\text{ASE}_{1000, 250h}$</td>
<td>$\text{ASE}_{1000, 250h}$</td>
</tr>
<tr>
<td>Overhang Length (ft.)</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Orientation</td>
<td>0° (S)</td>
<td>38.8%</td>
</tr>
<tr>
<td></td>
<td>45° (SE)</td>
<td>37.5%</td>
</tr>
<tr>
<td></td>
<td>90° (E)</td>
<td>34.4%</td>
</tr>
<tr>
<td></td>
<td>135° (NE)</td>
<td>9.4%</td>
</tr>
<tr>
<td></td>
<td>180° (N)</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>225° (NW)</td>
<td>17.0%</td>
</tr>
<tr>
<td></td>
<td>270° (W)</td>
<td>35.7%</td>
</tr>
<tr>
<td></td>
<td>315° (SW)</td>
<td>36.2%</td>
</tr>
</tbody>
</table>
Figure 4-1 Variations of ASE_{1000, 250h} of different window orientations, climate, and overhang lengths around 33°N

Figure 4-2 Variations of ASE_{1000, 250h} of different window orientations, climate, and overhang lengths around 40°N

Figure 4-3 Variations of ASE_{1000, 250h} of different window orientations, climate, and overhang lengths around 47°N
4.1.2 Discussion

![Diagram of cut-off angle](image)

**Figure 4-4** The cut-off angle illustration of the 5 ft overhang considering to the first row of analysis points

The results show that the overhang length does have some impact on the ASE. For all the cities, as the overhang length increases, the ASE in general goes lower except when the classroom window is facing north. According to LEED V4 criteria and the supporting research in LM-83-12, 10% ASE_{1000, 250h} is the maximum sunlight exposure permitted. Yet from the values obtained, none of the tested overhang lengths and bring the ASE_{1000, 250h} into the desirable range (below 10%) in most of the conditions. The overhang length changing from 0 ft to 5 ft did not result in a significant reduction in ASE_{1000, 250h}. The calculation method is illustrated in Figure 4-4. Similarly, the cut-off angles of the other overhang lengths in this research are listed in Table 4-4.

**Table 4-4 The cut-off angle of each overhang length to the first row of analysis points in this research**

<table>
<thead>
<tr>
<th>overhang length (ft.)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cut-off angle</td>
<td>63.4°</td>
<td>63.4°</td>
<td>57.3°</td>
<td>51.8°</td>
<td>47.1°</td>
<td>43.0°</td>
</tr>
</tbody>
</table>

The overhang length of 1 ft and the non-overhang condition have the same cut-off angle of 63.4°, indicating 1 ft overhang and non-overhang condition have the same impact on direct sunlight of which the incident angle is lower than 63.4°. It’s obvious that as the overhang length increases from 1 ft, the lower the cut-off angle becomes. The light beams with profile angles lower than the overhang cut-off angle penetrate into the room, and some of them contribute to the ASE_{1000, 250h}. Appendix A.3 provides the cumulative hours of the profile angles under each cut-off angle in Table 4-4 for each of the window orientations. The hours were calculated by the VBA module provided in Appendix B.2, and the functions implemented in this module are identical to ones in Appendix B.1. The cumulative hours decrease with the increase of overhang length, and the values reflect the direct sunlight penetration to some extent. The variations along different orientations show that the cumulative hours in east and west, southeast and southwest, as well as northeast and northwest are somewhat mirrored about the south direction. The slight differences between the mirrored pairs are due to the analysis period 8 AM to 6 PM not being symmetric with respect to solar noon.
Theoretically, according to the solar path (take 40°N as an example, illustrated in Figure 4-5), symmetry should happen about solar noon for south-facing space, where the sun is at the exact south direction of the classroom. The south facing window accumulates the most hours in a year, then the southeast, southwest, east, and west. It’s expected in the northern latitudes that the north facing window receives the least direct sunlight, which are validated by the data. In some of the locations, such as Denver and Pittsburgh, there is still direct sunlight penetration when the window is facing north in the early morning and late evening, illustrated in Figure 4-5. The phenomenon occurs at the two sites that are further north as well. The northeast direction has more cumulative hours than the northwest. The overhang length increase has more impact on the annual hours for the south facing window, as Figure A-1 to Figure A-3 show.

![Figure 4-5 Solar path at 40°N, red dotted lines are the analysis period in summer time, adapted from [2]](image)

The annual cumulative hours demonstrate the overall time when the direct sunlight will penetrate into the room, yet only takes into account the direct solar conditions in the temporal dimension, rather than the spatial dimension. That’s why ASE_{1000, 250h} is a better indicator in depicting the direct sunlight conditions in a space. The changes in ASE_{1000, 250h} can be attributed to the total time when the sunlight shoots into the room, and that’s just one factor. The ASE_{1000, 250h}, from its definition, denotes at least another two key factors: 1000 lux, and 250 hours. Whereas in the cumulative hours, it can be inferred how long time the sunlight stays inside the room, but how strong is it (whether or not the illuminance exceeds 1000 lux)? And where does the sunlight fall inside the room, on the same points or fall somewhere else as the time change? If on the same points, are the total hours more than 250 hours? These answers cannot be delivered directly from the accumulated hours, and the number only tells the total time the room has direct light under different overhang lengths. That’s why the patterns in the cumulative hours changing with orientations (V shape) look different from the patterns of the ASE_{1000, 250h} change (wing shape).
The sunlight illuminance condition is determined by the climate conditions, the sunshine hours over the year, and the solar altitude. The higher the solar altitude is, the larger the horizontal illuminance is under the same weather condition. The cities were divided into three groups in this study based on the latitude and under each latitude the sunshine hours are much different. It is apparent that the cities with more sunshine hours have larger overall ASE$_{1000, 250h}$ than those having fewer sunshine hours, as embodied from Figure 4-1 to Figure 4-3. The ‘wing’ of the cities with more clear skies is taller than the cities with more cloudy skies. Like the cumulative hours aforementioned, the north facing space has the lowest ASE$_{1000, 250h}$, since a north facing facade receives the least direct sunlight.

Around 33°N, both cities have the highest ASE$_{1000, 250h}$ when the window faces west, and the east face has the second high ASE$_{1000, 250h}$. The southeast and southwest facing conditions come next, and then south facing. The situation begins to change in the cities around 40°N, the values of southeast and southwest begin to catch up those of east and west facing. The situation in the cities around 47° is totally reversed compared to that of 33°.

The east and west facing spaces usually result in deeper sunlight penetration inside of a room, compared to the southeast/southwest and south-facing spaces. In the low latitude cities, the solar altitude angle is higher than for the cities at higher latitudes, which means the sunlight inside the room has a higher probability of exceeding 1000 lux, which gives rise to the higher ASE$_{1000, 250h}$ in east and west-facing rooms. The south-facing space usually sees a larger solar altitude angle making it harder for the sunlight to penetrate deeper inside the classroom in the lower latitude cities. As the latitude goes higher, the solar altitude begins to get lower at the same time of day, and the profile angles are below the cut-off angles for more hours, resulting in the ‘wing’ pattern transformation in the cities with similar sunshine conditions but different latitudes. There is an increase of ASE in S facades and an ASE decrease in E/NE facades as latitude increases. At 40°N, SE facing spaces have higher ASE and W/NW/SW facades have lower ASE compared to these directions at the other latitudes. In all 6 cities, the north facades always have zero ASE.

Some situations where the ASE did not change as the overhang was increased by 1 or 2 ft or even 3 ft since the increase in length does not have much impact on the points that counted for ASE$_{1000, 250h}$, since the grids are 2 ft by 2 ft rather than considered with a very dense spacing (i.e. a few millimeters). The study of latitudes ranging from 33°N to 47°N shows the trends of ASE changing with latitude and could provide some recommendations in the window orientation (especially in S, SE/SW, and E/W facing) selection considered at these site locations.
4.2 Analysis of sDA$_{300/50\%}$ with different shading devices

4.2.1 Simulation results of sDA$_{300/50\%}$ for roller shades with 5% VLT

The simulation of sDA$_{300/50\%}$ was time consuming and the simulation for roller shades and blinds were addressed in different approaches as aforementioned in Section 3.2. The sDA$_{300/50\%}$ for roller shades with 5% VLT simulation results for the 6 cities with 5 overhang lengths (non-overhang, 1ft to 4 ft in 1ft step) and 8 orientations are in Table 4-5, 4-6, and 4-7. The values are formatted by color scale with deeper red indicating a higher sDA. To make it more intuitive, sDA$_{300/50\%}$ for roller shades with 5% VLT changing with overhang lengths and window orientations are illustrated in Figure 4-6, 4-7, and 4-8. The axes and labels are set to the same scales as for the blindssDA$_{300/50\%}$ results in order to provide a clear comparison between these options.

Table 4-5 sDA$_{300/50\%}$ for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 33°N

<table>
<thead>
<tr>
<th>City (33°N)</th>
<th>Performance</th>
<th>Orientation</th>
<th>Overhang Length (ft.)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phoenix, AZ (more daylight hours)</td>
<td>sDA$_{300/50%}$</td>
<td>0° (S)</td>
<td>31.3%</td>
<td>32.6%</td>
<td>47.3%</td>
<td>58.5%</td>
<td>66.5%</td>
<td>42.9%</td>
<td>42.9%</td>
<td>53.6%</td>
<td>57.6%</td>
<td>62.1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>45° (SE)</td>
<td>38.4%</td>
<td>38.4%</td>
<td>47.3%</td>
<td>54.5%</td>
<td>60.3%</td>
<td>47.8%</td>
<td>47.8%</td>
<td>52.2%</td>
<td>56.3%</td>
<td>60.7%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° (E)</td>
<td>53.6%</td>
<td>53.6%</td>
<td>58.9%</td>
<td>60.7%</td>
<td>60.7%</td>
<td>54.0%</td>
<td>54.5%</td>
<td>56.7%</td>
<td>59.4%</td>
<td>59.4%</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>135° (NE)</td>
<td>61.6%</td>
<td>61.6%</td>
<td>61.6%</td>
<td>61.6%</td>
<td>61.2%</td>
<td>60.7%</td>
<td>60.7%</td>
<td>60.7%</td>
<td>61.2%</td>
<td>62.1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>180° (N)</td>
<td>67.4%</td>
<td>65.2%</td>
<td>64.7%</td>
<td>64.7%</td>
<td>62.5%</td>
<td>62.1%</td>
<td>61.6%</td>
<td>61.2%</td>
<td>61.2%</td>
<td>60.3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>225° (NW)</td>
<td>61.6%</td>
<td>61.6%</td>
<td>62.1%</td>
<td>61.6%</td>
<td>61.6%</td>
<td>60.7%</td>
<td>61.2%</td>
<td>61.2%</td>
<td>60.3%</td>
<td>60.7%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>270° (W)</td>
<td>52.2%</td>
<td>52.2%</td>
<td>54.5%</td>
<td>59.8%</td>
<td>59.8%</td>
<td>54.0%</td>
<td>56.3%</td>
<td>59.8%</td>
<td>59.8%</td>
<td>61.2%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>315° (SW)</td>
<td>30.8%</td>
<td>31.3%</td>
<td>41.1%</td>
<td>54.0%</td>
<td>60.7%</td>
<td>39.7%</td>
<td>41.1%</td>
<td>52.7%</td>
<td>58.0%</td>
<td>62.1%</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-6 sDA$_{300/50\%}$ for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 40°N

<table>
<thead>
<tr>
<th>City (40°N)</th>
<th>Performance</th>
<th>Orientation</th>
<th>Overhang Length (ft.)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denver, CO (more daylight hours)</td>
<td>sDA$_{300/50%}$</td>
<td>0° (S)</td>
<td>25.4%</td>
<td>27.2%</td>
<td>30.8%</td>
<td>32.6%</td>
<td>36.6%</td>
<td>45.1%</td>
<td>46.0%</td>
<td>51.8%</td>
<td>56.3%</td>
<td>59.8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>45° (SE)</td>
<td>28.1%</td>
<td>28.1%</td>
<td>30.8%</td>
<td>31.7%</td>
<td>35.3%</td>
<td>46.4%</td>
<td>46.4%</td>
<td>47.8%</td>
<td>52.7%</td>
<td>54.0%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° (E)</td>
<td>36.2%</td>
<td>36.2%</td>
<td>37.9%</td>
<td>39.7%</td>
<td>43.3%</td>
<td>52.2%</td>
<td>52.7%</td>
<td>53.6%</td>
<td>53.6%</td>
<td>54.5%</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>135° (NE)</td>
<td>49.6%</td>
<td>49.1%</td>
<td>51.3%</td>
<td>52.7%</td>
<td>50.9%</td>
<td>56.3%</td>
<td>55.8%</td>
<td>55.4%</td>
<td>55.4%</td>
<td>54.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>180° (N)</td>
<td>54.0%</td>
<td>53.6%</td>
<td>53.1%</td>
<td>52.7%</td>
<td>52.2%</td>
<td>58.0%</td>
<td>58.5%</td>
<td>58.0%</td>
<td>56.3%</td>
<td>54.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>225° (NW)</td>
<td>53.1%</td>
<td>52.2%</td>
<td>52.2%</td>
<td>53.1%</td>
<td>53.6%</td>
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<td>54.0%</td>
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</tr>
<tr>
<td></td>
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<td>270° (W)</td>
<td>46.4%</td>
<td>46.9%</td>
<td>48.7%</td>
<td>50.4%</td>
<td>52.2%</td>
<td>53.1%</td>
<td>53.6%</td>
<td>53.6%</td>
<td>54.9%</td>
<td>55.4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>315° (SW)</td>
<td>23.2%</td>
<td>23.2%</td>
<td>27.2%</td>
<td>31.7%</td>
<td>48.2%</td>
<td>42.4%</td>
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<td>48.2%</td>
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<td>55.8%</td>
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</table>

Table 4-7 sDA$_{300/50\%}$ for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 47°N

<table>
<thead>
<tr>
<th>City (47°N)</th>
<th>Performance</th>
<th>Orientation</th>
<th>Overhang Length (ft.)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fargo, ND (more daylight hours)</td>
<td>sDA$_{300/50%}$</td>
<td>0° (S)</td>
<td>25.4%</td>
<td>28.1%</td>
<td>40.2%</td>
<td>48.7%</td>
<td>53.6%</td>
<td>25.0%</td>
<td>27.2%</td>
<td>35.3%</td>
<td>39.7%</td>
<td>45.1%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>45° (SE)</td>
<td>37.1%</td>
<td>36.6%</td>
<td>40.2%</td>
<td>45.5%</td>
<td>46.9%</td>
<td>34.4%</td>
<td>35.3%</td>
<td>37.5%</td>
<td>39.3%</td>
<td>43.3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° (E)</td>
<td>47.8%</td>
<td>47.8%</td>
<td>51.3%</td>
<td>52.2%</td>
<td>51.8%</td>
<td>44.6%</td>
<td>45.1%</td>
<td>45.1%</td>
<td>44.6%</td>
<td>45.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>135° (NE)</td>
<td>53.1%</td>
<td>53.1%</td>
<td>52.7%</td>
<td>51.3%</td>
<td>52.2%</td>
<td>47.3%</td>
<td>46.9%</td>
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<td>46.9%</td>
<td>46.4%</td>
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<tr>
<td></td>
<td></td>
<td>180° (N)</td>
<td>54.5%</td>
<td>54.5%</td>
<td>54.5%</td>
<td>53.6%</td>
<td>52.7%</td>
<td>47.8%</td>
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<td>46.4%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>225° (NW)</td>
<td>50.9%</td>
<td>51.8%</td>
<td>52.2%</td>
<td>51.8%</td>
<td>50.9%</td>
<td>44.6%</td>
<td>44.2%</td>
<td>45.1%</td>
<td>45.5%</td>
<td>41.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>270° (W)</td>
<td>47.3%</td>
<td>47.8%</td>
<td>48.7%</td>
<td>50.0%</td>
<td>51.3%</td>
<td>38.8%</td>
<td>38.8%</td>
<td>40.2%</td>
<td>43.3%</td>
<td>43.8%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>315° (SW)</td>
<td>27.7%</td>
<td>28.1%</td>
<td>31.7%</td>
<td>41.1%</td>
<td>46.9%</td>
<td>25.4%</td>
<td>26.8%</td>
<td>29.3%</td>
<td>33.9%</td>
<td>37.9%</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4-6 Variations of \( sDA_{300:50\%} \) for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 33°N

Figure 4-7 Variations of \( sDA_{300:50\%} \) for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 40°N

Figure 4-8 Variations of \( sDA_{300:50\%} \) for roller shades with 5% VLT of different window orientations, climate, and overhang lengths around 47°N
4.2.2 Simulation results of $sDA_{300/50\%}$ for blinds with 20% VLT

The $sDA_{300/50\%}$ for blinds with 20% VLT simulation results for the 6 cities with 5 overhang lengths (non-overhang, 1ft to 4 ft in 1ft step) facing 8 orientations are recorded in Table 4-8, 4-9, and 4-10. The values are formatted by color scale with deeper red indicating a higher $sDA$. To make it more intuitive, $sDA_{300/50\%}$ for blinds with 20% VLT across the 6 cities and window orientations are illustrated in Figure 4-9, 4-10, and 4-11.

**Table 4-8 $sDA_{300/50\%}$ for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 33°N**

<table>
<thead>
<tr>
<th>City (33°N)</th>
<th>Phoenix, AZ (more daylight hours)</th>
<th>Birmingham, AL (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Performance</td>
<td>SDA$_{300%}$</td>
</tr>
<tr>
<td>0° (S)</td>
<td>0 1 2 3 4</td>
<td>67.3% 67.3% 75.4% 74.3% 75.0%</td>
</tr>
<tr>
<td>45° (SE)</td>
<td>0 1 2 3 4</td>
<td>69.1% 69.1% 72.3% 72.3% 72.0%</td>
</tr>
<tr>
<td>90° (E)</td>
<td>0 1 2 3 4</td>
<td>68.3% 68.3% 70.5% 68.3% 67.9%</td>
</tr>
<tr>
<td>135° (NE)</td>
<td>0 1 2 3 4</td>
<td>62.5% 62.5% 65.2% 61.6% 61.2%</td>
</tr>
<tr>
<td>180° (N)</td>
<td>0 1 2 3 4</td>
<td>67.4% 65.2% 64.7% 64.7% 62.5%</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>0 1 2 3 4</td>
<td>62.5% 62.9% 64.3% 62.9% 61.6%</td>
</tr>
<tr>
<td>270° (W)</td>
<td>0 1 2 3 4</td>
<td>71.0% 68.8% 71.4% 70.5% 68.3%</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>0 1 2 3 4</td>
<td>68.8% 68.8% 71.9% 73.2% 73.7%</td>
</tr>
</tbody>
</table>

**Table 4-9 $sDA_{300/50\%}$ for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 40°N**

<table>
<thead>
<tr>
<th>City (40°N)</th>
<th>Denver, CO (more daylight hours)</th>
<th>Pittsburgh, PA (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Performance</td>
<td>SDA$_{300%}$</td>
</tr>
<tr>
<td>0° (S)</td>
<td>0 1 2 3 4</td>
<td>62.9% 64.7% 67.9% 68.3% 68.8%</td>
</tr>
<tr>
<td>45° (SE)</td>
<td>0 1 2 3 4</td>
<td>60.3% 60.7% 61.2% 60.3% 59.4%</td>
</tr>
<tr>
<td>90° (E)</td>
<td>0 1 2 3 4</td>
<td>54.5% 54.9% 54.0% 54.0% 54.0%</td>
</tr>
<tr>
<td>135° (NE)</td>
<td>0 1 2 3 4</td>
<td>51.8% 51.8% 52.2% 52.7% 51.3%</td>
</tr>
<tr>
<td>180° (N)</td>
<td>0 1 2 3 4</td>
<td>54.0% 53.6% 53.6% 52.7% 52.2%</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>0 1 2 3 4</td>
<td>54.5% 54.0% 54.0% 54.5% 54.0%</td>
</tr>
<tr>
<td>270° (W)</td>
<td>0 1 2 3 4</td>
<td>62.1% 62.1% 62.5% 62.5% 62.1%</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>0 1 2 3 4</td>
<td>66.1% 66.1% 67.9% 68.8% 69.2%</td>
</tr>
</tbody>
</table>

**Table 4-10 $sDA_{300/50\%}$ for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 47°N**

<table>
<thead>
<tr>
<th>City (47°N)</th>
<th>Fargo, ND (more daylight hours)</th>
<th>Seattle, WA (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Performance</td>
<td>SDA$_{300%}$</td>
</tr>
<tr>
<td>0° (S)</td>
<td>0 1 2 3 4</td>
<td>59.8% 60.3% 66.5% 67.0% 67.4%</td>
</tr>
<tr>
<td>45° (SE)</td>
<td>0 1 2 3 4</td>
<td>61.6% 61.2% 61.6% 60.7% 60.3%</td>
</tr>
<tr>
<td>90° (E)</td>
<td>0 1 2 3 4</td>
<td>57.6% 56.7% 59.4% 58.0% 55.8%</td>
</tr>
<tr>
<td>135° (NE)</td>
<td>0 1 2 3 4</td>
<td>53.6% 54.0% 52.7% 51.3% 52.2%</td>
</tr>
<tr>
<td>180° (N)</td>
<td>0 1 2 3 4</td>
<td>54.5% 54.5% 53.6% 53.6% 52.7%</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>0 1 2 3 4</td>
<td>53.1% 53.1% 54.0% 52.7% 50.9%</td>
</tr>
<tr>
<td>270° (W)</td>
<td>0 1 2 3 4</td>
<td>58.9% 57.6% 58.9% 58.5% 57.1%</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>0 1 2 3 4</td>
<td>61.2% 61.2% 61.2% 60.7% 61.2%</td>
</tr>
</tbody>
</table>
Figure 4-9 Variations of $s_{DA,300/50}\%$ for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 33°N

Figure 4-10 Variations of $s_{DA,300/50}\%$ for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 40°N

Figure 4-11 Variations of $s_{DA,300/50}\%$ for blinds with 20% VLT of different window orientations, climate, and overhang lengths around 47°N
4.2.3 Simulation results of sDA$_{300/50\%}$ for blinds in real geometry with 80% reflectance

The sDA$_{300/50\%}$ for blinds in real geometry with 80% reflectance simulation results for the 6 cities with 5 overhang lengths (non-overhang, 1ft to 4 ft in 1ft step) facing 8 orientations are recorded in Table 4-11, 4-12, and 4-13. The values are formatted by color scale with deeper red indicating a higher sDA. To make it more intuitive, sDA$_{300/50\%}$ for blinds with 80% reflectance across the 6 cities and window orientations are illustrated in Figure 4-12, 4-13, and 4-14.

**Table 4-11 sDA$_{300/50\%}$ for blinds with 80% reflectance of different window orientations, climate, and overhang lengths around 33°N**

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Performance</th>
<th>SDA$_{300/50%}$</th>
<th>SDA$_{50%}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>City (33°N)</td>
<td>Phoenix, AZ (more daylight hours)</td>
<td>Birmingham, AL (less daylight hours)</td>
<td></td>
</tr>
<tr>
<td>Overhang Length (ft.)</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0° (S)</td>
<td>60.3%</td>
<td>60.7%</td>
<td>61.2%</td>
</tr>
<tr>
<td>45° (SE)</td>
<td>59.4%</td>
<td>59.8%</td>
<td>61.2%</td>
</tr>
<tr>
<td>90° (E)</td>
<td>61.2%</td>
<td>61.2%</td>
<td>63.8%</td>
</tr>
<tr>
<td>135° (NE)</td>
<td>62.1%</td>
<td>62.1%</td>
<td>63.8%</td>
</tr>
<tr>
<td>180° (N)</td>
<td>67.0%</td>
<td>66.5%</td>
<td>65.6%</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>67.4%</td>
<td>66.5%</td>
<td>65.6%</td>
</tr>
<tr>
<td>270° (W)</td>
<td>68.3%</td>
<td>68.3%</td>
<td>68.8%</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>67.4%</td>
<td>67.9%</td>
<td>68.8%</td>
</tr>
</tbody>
</table>

**Table 4-12 sDA$_{300/50\%}$ for blinds with 80% reflectance of different window orientations, climate, and overhang lengths around 40°N**

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Performance</th>
<th>SDA$_{300/50%}$</th>
<th>SDA$_{50%}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>City (40°N)</td>
<td>Denver, CO (more daylight hours)</td>
<td>Pittsburgh, PA (less daylight hours)</td>
<td></td>
</tr>
<tr>
<td>Overhang Length (ft.)</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0° (S)</td>
<td>62.5%</td>
<td>62.5%</td>
<td>62.1%</td>
</tr>
<tr>
<td>45° (SE)</td>
<td>54.9%</td>
<td>57.1%</td>
<td>57.1%</td>
</tr>
<tr>
<td>90° (E)</td>
<td>53.1%</td>
<td>52.7%</td>
<td>53.1%</td>
</tr>
<tr>
<td>135° (NE)</td>
<td>53.6%</td>
<td>54.0%</td>
<td>54.0%</td>
</tr>
<tr>
<td>180° (N)</td>
<td>57.1%</td>
<td>56.3%</td>
<td>55.4%</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>61.6%</td>
<td>60.7%</td>
<td>60.7%</td>
</tr>
<tr>
<td>270° (W)</td>
<td>61.2%</td>
<td>60.7%</td>
<td>61.2%</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>61.2%</td>
<td>61.2%</td>
<td>61.2%</td>
</tr>
</tbody>
</table>

**Table 4-13 sDA$_{300/50\%}$ for blinds 80% reflectance of different window orientations, climate, and overhang lengths around 47°N**

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Performance</th>
<th>SDA$_{300/50%}$</th>
<th>SDA$_{50%}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>City (47°N)</td>
<td>Fargo, ND (more daylight hours)</td>
<td>Seattle, WA (less daylight hours)</td>
<td></td>
</tr>
<tr>
<td>Overhang Length (ft.)</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>0° (S)</td>
<td>61.0%</td>
<td>62.1%</td>
<td>61.0%</td>
</tr>
<tr>
<td>45° (SE)</td>
<td>55.4%</td>
<td>55.4%</td>
<td>56.7%</td>
</tr>
<tr>
<td>90° (E)</td>
<td>54.5%</td>
<td>54.0%</td>
<td>55.8%</td>
</tr>
<tr>
<td>135° (NE)</td>
<td>54.5%</td>
<td>54.0%</td>
<td>54.0%</td>
</tr>
<tr>
<td>180° (N)</td>
<td>54.0%</td>
<td>54.0%</td>
<td>53.6%</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>54.5%</td>
<td>54.0%</td>
<td>54.0%</td>
</tr>
<tr>
<td>270° (W)</td>
<td>57.1%</td>
<td>56.7%</td>
<td>55.4%</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>58.0%</td>
<td>58.9%</td>
<td>58.0%</td>
</tr>
</tbody>
</table>
Figure 4-12 Variations of $sDA_{300/50\%}$ for blinds with 80% reflectance of different window orientations, climate, and overhang lengths around 33°N

Figure 4-13 Variations of $sDA_{300/50\%}$ for blinds with 80% reflectance of different window orientations, climate, and overhang lengths around 40°N

Figure 4-14 Variations of $sDA_{300/50\%}$ for blinds with 80% reflectance of different window orientations, climate, and overhang lengths around 47°N
4.2.4 Discussion

The first impression of the figures in Section 4.2.1 to 4.2.3 is that the $sDA_{300/50\%}$ for blinds have a much gentler slope than those for roller shades indicating $sDA_{300/50\%}$ is easier to be maintained at a relatively constant value across all 8 directions. In the conditions where blinds are implemented, the $sDA_{300/50\%}$ values across different orientations are similar, without a huge gap, which is most similar to the 4 ft overhang in the roller shade condition.

Under roller shade conditions, it’s obvious that the $sDA_{300/50\%}$ for the S/SE/E/SW/W facing spaces with fewer sunshine hours is higher than those cities in the same latitude group around 33°N and 40°N. That’s because roller shades only act when there is direct sunlight while under the cloudy skies, roller shades are less likely to be operated, which allow more diffuse light to go into the room. When blinds are implemented, the results of $sDA_{300/50\%}$ for the S/SE/E/SW/W facing spaces in the cities around 33°N and 40°N are no longer the same with those of roller shade conditions. This is due to larger transmittance of blinds allowing more light into the room, although the blinds are lowered under the same conditions as the roller shades.

In the cities around 47°N, all shading devices result in higher $sDA_{300/50\%}$ in Fargo (with more sunshine hours) than in Seattle (with less sunshine hours). The reason is that Seattle has too much rain and the illuminance contribution from the sky is much lower than that of Fargo even though there are more shades down hours in Fargo, as listed in Table 4-16.

The $sDA_{300/50\%}$ calculation accounts for on and off control of the shading device, and the program automatically pulls down the shades or blinds to restrict the direct sunlight penetration inside the room to 2% or less. With the implementation of an overhang, the roller shades tend to be pulled down for less time as the overhang gets longer. The number of hours shades are down in the analysis period throughout a year in the 6 cities are listed in Table 4-14 to Table 4-16. The variations in the number of hours above are demonstrated in Figure A-4, Figure A-5, and Figure A-6.

In the S/SE/SW/E/W facing spaces, $sDA_{300/50\%}$ for roller shades increases as the overhang length increases since the fixed shading device reduces the need for interior shading. In the N/NE/NW facing spaces, the situation is reversed since the shades are less likely to be down at these orientations and the longer overhang blocks daylight from going deeper into the room.

In most of the cities, as shown in Figure 4-6 and Figure 4-7, $sDA_{300/50\%}$ for roller shades in the S/SE/E/SW/W directions is easily increased by adding overhang length, while in Denver, this pattern is not so obvious. One reason might be the climate differences in different cities. Another reason might be that roller shades going down too often prevents the diffuse light from going deeper into the room. To make it more clear, Denver and Fargo at a south facing condition can be taken as an example. From the $sDA_{300/50\%}$
results in Table 4-6 and 4-7, sDA$_{300/50\%}$ in Denver changes from 25.4% to 35.6%, while in Fargo the sDA$_{300/50\%}$ changes from 25.4% to 53.6% when the overhang length is increased from 0 ft to 4 ft.

In both of the cities at 0 ft overhang length, the shades are on in more than half of the analysis periods according to Table 4-15 and Table 4-16. When the overhang length is increased to 4 ft in both cities, the decrease in hours of shades-on condition in Fargo (621 hours) is slightly more than that in Denver (601 hours). Thus the diffuse light has more opportunity to get into the room in Fargo than Denver, which can result in a greater increase in sDA. Figure 4-15 created by the Matlab script attached in Appendix B.4 intuitively show the shades option during the analysis period while the overhang length is changing from 0 ft to 4 ft.

**Table 4-14 Number of hours shades are down in the analysis period throughout a year in cities around 33°N**

<table>
<thead>
<tr>
<th>City (33°N)</th>
<th>Phoenix, AZ (more daylight hours)</th>
<th>Birmingham, AL (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhang Length (ft.)</td>
<td>Performance</td>
<td>Hours</td>
</tr>
<tr>
<td>0° (S)</td>
<td>1781</td>
<td>1676</td>
</tr>
<tr>
<td>45° (SE)</td>
<td>1671</td>
<td>1664</td>
</tr>
<tr>
<td>90° (E)</td>
<td>1214</td>
<td>1214</td>
</tr>
<tr>
<td>135° (NE)</td>
<td>586</td>
<td>560</td>
</tr>
<tr>
<td>180° (N)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>527</td>
<td>527</td>
</tr>
<tr>
<td>270° (W)</td>
<td>1123</td>
<td>1115</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>1593</td>
<td>1565</td>
</tr>
</tbody>
</table>

**Table 4-15 Number of hours shades are down in the analysis period throughout a year in cities around 40°N**

<table>
<thead>
<tr>
<th>City (40°N)</th>
<th>Denver, CO (more daylight hours)</th>
<th>Pittsburgh, PA (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhang Length (ft.)</td>
<td>Performance</td>
<td>Hours</td>
</tr>
<tr>
<td>0° (S)</td>
<td>1884</td>
<td>1839</td>
</tr>
<tr>
<td>45° (SE)</td>
<td>1661</td>
<td>1637</td>
</tr>
<tr>
<td>90° (E)</td>
<td>1001</td>
<td>986</td>
</tr>
<tr>
<td>135° (NE)</td>
<td>398</td>
<td>398</td>
</tr>
<tr>
<td>180° (N)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>455</td>
<td>455</td>
</tr>
<tr>
<td>270° (W)</td>
<td>1093</td>
<td>1076</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>1708</td>
<td>1695</td>
</tr>
</tbody>
</table>

**Table 4-16 Number of hours shades are down in the analysis period throughout a year in cities around 47°N**

<table>
<thead>
<tr>
<th>City (47°N)</th>
<th>Fargo, ND (more daylight hours)</th>
<th>Seattle, WA (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhang Length (ft.)</td>
<td>Performance</td>
<td>Hours</td>
</tr>
<tr>
<td>0° (S)</td>
<td>1751</td>
<td>1710</td>
</tr>
<tr>
<td>45° (SE)</td>
<td>1446</td>
<td>1446</td>
</tr>
<tr>
<td>90° (E)</td>
<td>921</td>
<td>921</td>
</tr>
<tr>
<td>135° (NE)</td>
<td>312</td>
<td>312</td>
</tr>
<tr>
<td>180° (N)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>316</td>
<td>297</td>
</tr>
<tr>
<td>270° (W)</td>
<td>837</td>
<td>830</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>1433</td>
<td>1422</td>
</tr>
</tbody>
</table>
Figure 4-15 Shade operation at south facing changing from 0 ft overhang to 4 ft overhang over 3650 hours. The light color bars show that the shades are down and the dark color bars mean shades are up.
The annual sunshine hours map only shows a range of sunshine hours per year. In this research, according to the weather files apply in these simulations, the annual sunlight hours for each city based on a calculation of exterior ground illuminance (zero bounces, illuminance greater than 1000 lux is counted for an hour) are shown as Table 4-17.

**Table 4-17 Annual sunlight hours of each city based on calculation**

<table>
<thead>
<tr>
<th>Location</th>
<th>Phoenix, AZ</th>
<th>Birmingham, AL</th>
<th>Denver, CO</th>
<th>Pittsburgh, PA</th>
<th>Fargo, ND</th>
<th>Seattle, WA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Sunlight hours</td>
<td>3219</td>
<td>2629</td>
<td>3062</td>
<td>2186</td>
<td>2507</td>
<td>2068</td>
</tr>
</tbody>
</table>

The higher sDA$_{300/50\%}$ for the roller shades condition usually occurs in the NW/N/NE orientations compared with S/SE/E/SW/W directions, whereas in sDA$_{300/50\%}$ for the blinds condition, the S/SE/E/SW/W tends to have higher values. Under blind conditions, the sDA$_{300/50\%}$ results are less likely to be affected by the overhang length. The blinds in general have better sDA$_{300/50\%}$ results than those of roller shades, especially in the south facing space. That’s because the blind rotation angles are adjusted to lower angles for a south orientation than others based on the profile angle criteria (Appendix A.2), which results in more diffuse light coming into the space.

For the two approaches in modeling blinds, most sDA$_{300/50\%}$ results for 20% VLT are higher than the real geometry blinds in S/SE/E/SW/W directions. This advantage is greater as the overhang length increases and even 75% sDA$_{300/50\%}$ is achieved in Phoenix with a 4 ft overhang when the space is facing south. In the cities around 40°N, N/NE/NW facing spaces modeled by 20% VLT have lower sDA$_{300/50\%}$ than those modeled by real geometry, and similar results extend to the cities around 47°N with NE/NW facing windows. Overall, the real geometry blind sDA$_{300/50\%}$ simulation is more time consuming when taking into account rotation angle month by month. The simplified approach of 20% VLT takes less time and the differences are not large compared to the real blind simulation.

**4.3 Recommendations for improving the daylight performance in a classroom**

The achievement of LEED V4 credit for daylight, which considers both Spatial Daylight Autonomy and Annual Sunlight Exposure, is challenging for the classroom investigated in this thesis.

In real geometry blind modeling, only the cities in low latitude (33°N) have a chance to get 2 points, achieving 65% sDA$_{300/50\%}$ in S/SW/W/N/NW orientations. In blinds with 20% VLT simulations, the range of cities was extended to northern latitudes with longer overhang. 75% sDA$_{300/50\%}$ was achieved by implementing a 20% VLT modeling approach in this research. Another big issue in getting this credit is the requirement to achieve ASE$_{1000, 250\text{h}}$ below 10%. Even with the overhang lengthened to 5 ft, it was still difficult to restrain ASE$_{1000, 250\text{h}}$ within 10% in the S/SE/E/SW/W directions.
The results from the simulation can provide some guidelines in improving the daylight performance when an overhang is implemented as an exterior shading device. The first is the selection of window facing orientation. The NE/N/NW facing spaces have a lower $\text{ASE}_{1000, 250h}$ and a relatively high $\text{sDA}_{300/50\%}$. In the low latitude sights, south facing is another choice with longer overhangs. The SW/SE/W/E orientations should be avoided in higher latitude areas, but if selected, use a longer overhang with shading devices.

The second is the selection of shading devices, if ASE is an issue, the shading devices should be implemented, and blinds tend to provide better results in $\text{sDA}_{300/50\%}$ than the roller shades due to their higher transmittance. The longer overhang will help to reduce the direct sunlight.

The third consideration is the climate impact. $\text{ASE}_{1000, 250h}$ is a good parameter with which to evaluate the tendency of a space to receive direct sunlight and the $\text{sDA}_{300/50\%}$ is a good denotation of the daylight penetration inside of a room. In a real design, even if the latitude is similar between sites, the climate impact is not trivial. A study in local climate is essential before design, since the adjustment of geometry may give rise to better daylight performance and budget savings in the materials such as the length of overhang, the aperture size and so on.

The recommendations above can make it easier for the designers to optimize a design. In a practical design sense, it’s important to run the simulations for different scenarios because sometimes the results might be a little unexpected.
Chapter 5 Conclusions

5.1 Daylight conditions in a classroom space with an overhang: A perspective

The daylight is dynamic inside a space, and it’s not easy to evaluate it in a single, comprehensive metric. This study investigated the two metrics in a classroom, sDA\textsubscript{300/50\%} and ASE\textsubscript{1000.250h}, provided by IES-LM 83-12. The simulation results show how the two metrics changed with variables, i.e. location, window orientation, overhang length, climate, and shading device type. Findings of this research are summarized below:

- The location of the 6 cities, in terms of latitude differences, can affect ASE and sDA when analyzed comprehensively with window orientation and different overhang length. The locations and window orientations are coupled with different solar angles like solar altitude angle and solar profile angle. Higher solar altitude angle provides higher illuminance from sunlight. Lower profile angle means sunlight has more chances to penetrate deeper into the space. The overhang is a useful exterior shading device to block sunlight by eliminating sunlight based on solar profile angle. N/NW/NE facing spaces have lower ASE as there is less sunlight penetration. E/W orientations have a higher potential of being exposed to more sunlight because of low profile angles near sunrise and sunset. The ASE in S/SW directions increases with latitude due to lower profile angles in more northern latitudes. The ASE in NE/E facades, however, decreases with latitude due to lower solar altitude angles even though the solar profile angles go lower as latitude goes more northern. Due to the impacts of locations and window orientations on both solar altitude and profile angles, the ASE at 40°N has higher values in SE while lower values in W/NW than the corresponding directions at the other two latitudes. North facing spaces always have a zero ASE since the north facing spaces receive very little direct sunlight. As the overhang is a fixed shading device included in an ASE calculation, the longer overhang blocks more sunlight thus is likely to lower ASE.

- The analysis of sDA is more comprehensive, by taking not only the above factors impacting ASE into account, but also the impact of interior shading devices such as shades and blinds. The operation threshold of both translucent shades and blinds is the same, which is to restrict direct sunlight to 2% or less inside the space. The frequency of shading device operation alters the overall illuminance in the space and thus can change sDA\textsubscript{300/50\%}. The implementation of longer overhangs can help to reduce the interior shades-down hours, and often raises the sDA in directions (S/SW/SE/E/W) where sunlight is incident on the roller shades or blinds. Whereas in orientations (N/NE/NW) with less direct sunlight, the overhang length increase might lower the sDA a little (within 5%).

- The climate considerations in this research focused on how much sunshine (annual sunlight hours listed in Table 4-17) the site experiences. The daylight illuminance in the room is contributed from sunlight
and diffuse light (mainly comes from the sky). The illuminance counted for ASE is for sunlight only, thus the cities with more sunshine hours per year appear to have higher $\text{ASE}_{1000, 250h}$ than those with less exposure time. The risk of having visual discomfort is therefore higher in Phoenix, Denver, and Fargo.

- The contribution of climate to sDA, however, is more complicated than with ASE, since the sDA calculation considers not only direct sunlight (limited to no more than 2% of the work plane), but the diffuse light distributed by shading devices as well. The impact of climate on sDA is affected by the operation hours of shading devices. The more sunshine hours, the more frequently shading devices are down when other variables (latitude, orientation, and overhang length) are the same.

- Different shading devices have different transmittance, blinds with higher transmittance will obviously provide better results in sDA (especially in S/SW/SE/E/W directions) than roller shades with only 5% transmittance (which is the default in LM-83) as more diffuse light enters the room. The two different approaches in modeling blinds showed results without big differences. The real geometry modeling tends to have better results in NE/NW than the simplified (20% VLT) modeling, otherwise there are only minor differences.

The variables in the above findings are entangled such that a small change of one factor may result in a significant difference in the resulting metric. That’s why, in design, all factors need to be considered together. N/NW/NE are preferred window facing orientations for achieving both good $\text{sDA}_{300/50\%}$ and $\text{ASE}_{1000, 250h}$ results. For the other directions, obtaining $\text{ASE}_{1000, 250h}$ below 10%, as required by LEED V4, is a challenge, and in most cases is not possible with a simple overhang.

$s\text{DA}_{300/50\%}$ and $\text{ASE}_{1000, 250h}$ are considered together in evaluating daylight performance inside a given space. Each metric includes three dimensions: illuminance threshold, temporal threshold and spatial threshold. The introduction of spatial characterization makes sDA and ASE more advanced in evaluating daylight within an analysis area than conventional metrics that do not consider area coverage like DA, cDA. sDA and ASE should be always used together as they provide important information by quantifying the daylight illuminance sufficiency and risk of too much sunlight penetration respectively.

### 5.2 Limitations and future work

There are some limitations on this research and some future work that can be done to expand the research.

- This research did not take into consideration any energy factors in the daylight design evaluation. The purpose of daylight design is not only for user comfort but also for energy savings on electric light. Future evaluations can integrate the electric light and other energy factors such as heating and cooling loads together.
- ASE$_{1000, 250h}$ only shows the potential risk of visual discomfort. If roller shades or blinds are installed, the risks may be eliminated as the shading device is constraining the direct sunlight penetration to 2% or less. The zero ASE$_{1000, 250h}$ in this research for north-facing spaces does not mean occupants never receive visual discomfort caused by direct sunlight. Think of an extreme example: the illuminance of points covering very large area exceeds 1000 lux in 249 hours per year (zero ASE$_{1000, 250h}$) have no big difference in visual experience with those of 250 hours per year (ASE$_{1000, 250h}$ might be very high). A view of a very bright exterior surround or sky can also cause daylight glare.

- Daylight glare can result from overly bright shading devices, which is not addressed by either sDA or ASE and was not studied in this research.

- The cities were grouped by 3 latitudes, and different climate conditions. It was a scientific and rigorous lateral comparison of sDA$_{300/50\%}$ and ASE$_{1000, 250h}$ with similar latitude but different climate since climate is the only variable. For the longitudinal comparison, it is better that the climate (mainly sunshine hours, but also the magnitude of the cloud-cover conditions) is the same for the cities in different latitudes, so that the climate factor can be excluded when analyzing other variables.

- The overhang with different lengths in this study did not significantly improve ASE in the S/SW/SE directions. In the future, alternate exterior shading devices, such as a light shelf, louvers, etc. can be investigated to see if they provide better performance.

- The blind rotation angle is usually adjusted by the occupants, so the performance registered by sDA might not reflect real world conditions well since it involves manually rotating the blinds to precise angles month by month, and using the critical angle required for the worst daylight condition during that entire month.

- No furniture or partitions were considered in the simulation in order to simplify the process. Furniture or partitions can be added in the future, however, according to LM-83, spaces such as a classroom can be modeled without furniture since its height is below 3 ft.
BIBLIOGRAPHY


### Appendix A: Supplemental tables and figures

#### A.1 Minimum solar profile angles between 8 AM to 6 PM for each city

*Table A-1 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Phoenix*

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*Table A-2 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Birmingham*

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*Table A-3 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Denver*

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### Table A-4 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Pittsburgh

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### Table A-5 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Fargo

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### Table A-6 The lowest profile angle between 8 AM to 6 PM in each month with different window facing orientation in Seattle

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A.2 Blind rotation angles in 12 months for each city

**Table A-7 The cut-off angle of 0° to 60° blind rotation and the maximum overhang length for sDA calculation**

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**Table A-8 The rotation angle selected in each month with different window facing orientation in Phoenix**

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**Table A-9 The rotation angle selected in each month with different window facing orientation in Birmingham**

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**Table A-10 The rotation angle selected in each month with different window facing orientation in Denver**

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<td>60°</td>
<td>60°</td>
<td>30°</td>
<td>0°</td>
<td>30°</td>
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</tr>
</tbody>
</table>
### Table A-11 The rotation angle selected in each month with different window facing orientation in Pittsburgh

<table>
<thead>
<tr>
<th>Pittsburgh</th>
<th>0° (S)</th>
<th>45° (SE)</th>
<th>90° (E)</th>
<th>135° (NE)</th>
<th>180° (N)</th>
<th>225° (NW)</th>
<th>270° (W)</th>
<th>315° (SW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>60°</td>
<td>60°</td>
<td>60°</td>
<td>60°</td>
<td>0°</td>
<td>60°</td>
<td>60°</td>
<td>60°</td>
</tr>
<tr>
<td>February</td>
<td>60°</td>
<td>60°</td>
<td>60°</td>
<td>60°</td>
<td>0°</td>
<td>45°</td>
<td>60°</td>
<td>60°</td>
</tr>
<tr>
<td>March</td>
<td>60°</td>
<td>60°</td>
<td>60°</td>
<td>60°</td>
<td>0°</td>
<td>30°</td>
<td>60°</td>
<td>60°</td>
</tr>
<tr>
<td>April</td>
<td>0°</td>
<td>60°</td>
<td>60°</td>
<td>60°</td>
<td>0°</td>
<td>0°</td>
<td>30°</td>
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<tr>
<td>May</td>
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<td>30°</td>
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</tr>
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<td>15°</td>
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<td>15°</td>
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<td>July</td>
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<td>0°</td>
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<td>August</td>
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<td>45°</td>
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<td>September</td>
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<td>45°</td>
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<tr>
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<td>0°</td>
<td>0°</td>
<td>60°</td>
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</tr>
<tr>
<td>November</td>
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<td>60°</td>
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<td>45°</td>
<td>0°</td>
<td>60°</td>
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<td>60°</td>
<td>60°</td>
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</table>

### Table A-12 The rotation angle selected in each month with different window facing orientation in Fargo

<table>
<thead>
<tr>
<th>Fargo</th>
<th>0° (S)</th>
<th>45° (SE)</th>
<th>90° (E)</th>
<th>135° (NE)</th>
<th>180° (N)</th>
<th>225° (NW)</th>
<th>270° (W)</th>
<th>315° (SW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
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<td>60°</td>
<td>60°</td>
<td>0°</td>
<td>60°</td>
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<td>February</td>
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<td>60°</td>
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<tr>
<td>March</td>
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<td>60°</td>
<td>60°</td>
<td>60°</td>
<td>0°</td>
<td>60°</td>
<td>60°</td>
<td>60°</td>
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<tr>
<td>April</td>
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<td>30°</td>
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<tr>
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### Table A-13 The rotation angle selected in each month with different window facing orientation in Seattle

<table>
<thead>
<tr>
<th>Seattle</th>
<th>0° (S)</th>
<th>45° (SE)</th>
<th>90° (E)</th>
<th>135° (NE)</th>
<th>180° (N)</th>
<th>225° (NW)</th>
<th>270° (W)</th>
<th>315° (SW)</th>
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</thead>
<tbody>
<tr>
<td>January</td>
<td>60°</td>
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<td>60°</td>
<td>60°</td>
<td>0°</td>
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<td>45°</td>
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<td>0°</td>
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</table>
A.3 Annual hours of profile angles below the cut-off angles of overhang for each city

**Table A-14** Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length for the cities around 33°N

<table>
<thead>
<tr>
<th>City (33°N)</th>
<th>Phoenix, AZ (more daylight hours)</th>
<th>Birmingham, AL (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Performance</td>
<td>Hours</td>
</tr>
<tr>
<td></td>
<td>Overhang Length (ft.)</td>
<td>0 1 2 3 4 5</td>
</tr>
<tr>
<td>0° (S)</td>
<td>2057</td>
<td>2057 1836 1640 1464 1300</td>
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<tr>
<td>45° (SE)</td>
<td>2004</td>
<td>2004 1743 1538 1342 1175</td>
</tr>
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<td>90° (E)</td>
<td>1471</td>
<td>1471 1208 1123 1045 1016</td>
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<tr>
<td>135° (NE)</td>
<td>852</td>
<td>852 632 603 603 0</td>
</tr>
<tr>
<td>180° (N)</td>
<td>112</td>
<td>112 87 49 0 0</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>394</td>
<td>394 357 168 127 127</td>
</tr>
<tr>
<td>270° (W)</td>
<td>1016</td>
<td>1016 951 776 663 589</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>1548</td>
<td>1548 1309 1083 907 769</td>
</tr>
</tbody>
</table>

**Table A-15** Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length for the cities around 40°N

<table>
<thead>
<tr>
<th>City (40°N)</th>
<th>Denver, CO (more daylight hours)</th>
<th>Pittsburgh, PA (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Performance</td>
<td>Hours</td>
</tr>
<tr>
<td></td>
<td>Overhang Length (ft.)</td>
<td>0 1 2 3 4 5</td>
</tr>
<tr>
<td>0° (S)</td>
<td>2234</td>
<td>2234 1991 1783 1615 1458</td>
</tr>
<tr>
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<td>2014</td>
<td>2014 1791 1560 1379 1179</td>
</tr>
<tr>
<td>90° (E)</td>
<td>1407</td>
<td>1407 1204 1120 1099 919</td>
</tr>
<tr>
<td>135° (NE)</td>
<td>657</td>
<td>657 603 555 471 342</td>
</tr>
<tr>
<td>180° (N)</td>
<td>0</td>
<td>0 0 0 0 0</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>451</td>
<td>451 390 277 160</td>
</tr>
<tr>
<td>270° (W)</td>
<td>1224</td>
<td>1224 933 818 735</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>1828</td>
<td>1828 1608 1372 1192 990</td>
</tr>
</tbody>
</table>

**Table A-16** Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length for the cities around 47°N

<table>
<thead>
<tr>
<th>City (47°N)</th>
<th>Fargo, ND (more daylight hours)</th>
<th>Seattle, WA (less daylight hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientation</td>
<td>Performance</td>
<td>Hours</td>
</tr>
<tr>
<td></td>
<td>Overhang Length (ft.)</td>
<td>0 1 2 3 4 5</td>
</tr>
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<td>0° (S)</td>
<td>2497</td>
<td>2497 2200 1983 1807 1654</td>
</tr>
<tr>
<td>45° (SE)</td>
<td>2309</td>
<td>2309 2120 1911 1722 1562</td>
</tr>
<tr>
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<td>1485</td>
<td>1485 1405 1280 1195 1110</td>
</tr>
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<td>786 623 560 530 530</td>
</tr>
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<td>180° (N)</td>
<td>10</td>
<td>10 0 0 0 0</td>
</tr>
<tr>
<td>225° (NW)</td>
<td>339</td>
<td>339 129 107 86</td>
</tr>
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<td>270° (W)</td>
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<td>1034 948 832 747 685</td>
</tr>
<tr>
<td>315° (SW)</td>
<td>1864</td>
<td>1864 1677 1477 1276 1115</td>
</tr>
</tbody>
</table>
Figure A-1 Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length changing with orientations for the cities around 33°N

Figure A-2 Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length changing with orientations for the cities around 40°N

Figure A-3 Annually cumulative hours between 8 AM to 6 PM of profile angles below the cut-off angles of each overhang length changing with orientations for the cities around 47°N
A.4 Annual hours of shades down in the analysis period for each city

**Figure A-4** Variations in number of hours shades are down in the analysis period throughout a year in cities around 33°N

**Figure A-5** Variations in number of hours shades are down in the analysis period throughout a year in cities around 40°N

**Figure A-6** Variations in number of hours shades are down in the analysis period throughout a year in cities around 47°N
Appendix B:   Important subroutines used in the simulation

B.1 Minimum solar profile angles calculation between 8 AM to 6 PM for each city (VBA)

B.1.1 Func_CalcAp

'Calculate solar profile angle, all angles in radians
Function CalcAp(At As Double, Az As Double) As Double
Tan(At)))
End Function

B.1.2 Func_CalcAs

'Calculate solar elevation azimuth angle, all angles in radians
Function CalcAs(DEC As Double, Lt As Double, SoT As Double) As Double
CalcAs = Application.WorksheetFunction.Atan2((-Cos(Lt) * Sin(DEC) + Sin(Lt) * Cos(DEC) 
* Cos(Application.WorksheetFunction.Pi() * SoT / 12)), -Cos(DEC) * 
Sin(Application.WorksheetFunction.Pi() * SoT / 12))
End Function

B.1.3 Func_CalcAt

'Calculate the altitude angle, all in radians
Function CalcAt(Lt As Double, DEC As Double, SoT As Double) As Double
CalcAt = Application.WorksheetFunction.Asin(Sin(Lt) * Sin(DEC) - Cos(Lt) * Cos(DEC) * 
Cos(Application.WorksheetFunction.Pi() * SoT / 12))
End Function

B.1.4 Func_CalcSoT

'Calculate solar time
Function CalcSoT(ST As Double, ET As Double, SM As Double, Lg As Double) As Double
CalcSoT = ST + ET + 12 * (SM - Lg) / 180
End Function

B.1.5 Main_min.profileangle

'Subroutine to compute profile angles
Sub Computeprofileangles()
Dim Lg(6) As Double
Dim Lt(6) As Double
Dim SM(6) As Double
Dim Jstart As Double
Dim Jend As Double
Dim ST(10, 365) As Double
Dim ET(365) As Double
Dim SoT(6, 10, 365) As Double
Dim DEC(365) As Double
Dim At(6, 10, 365) As Double
Dim Az(6, 6, 10, 365) As Double
Dim Ap(8, 6, 10, 365) As Double
Dim h As Integer               '10 hours
Dim i As Integer               '6 locations
Dim J As Integer '365 days
Dim k As Integer '8 elevation azimuths
Dim m As Integer '12 month
Dim Min As Double

With Sheets("Input")
Jstart = .Cells(11, 5)
Jend = .Cells(12, 5)
Ae(1) = 0
Ae(2) = Application.WorksheetFunction.Pi() / 4
Ae(3) = Application.WorksheetFunction.Pi() / 2
Ae(4) = Application.WorksheetFunction.Pi() / 4 * 3
Ae(5) = Application.WorksheetFunction.Pi()
Ae(6) = (Application.WorksheetFunction.Pi() / 4 * 3)
Ae(7) = (Application.WorksheetFunction.Pi() / 2)
Ae(8) = (Application.WorksheetFunction.Pi() / 4)

For J = 1 To 365
ET(J) = .Cells(J + 2, 13)
DEC(J) = .Cells(J + 2, 14)
If J >= Jstart And J < Jend Then
For h = 1 To 10
ST(h, J) = .Cells(2 + h, 10)
Next h
Else
For h = 1 To 10
ST(h, J) = .Cells(2 + h, 9)
Next h
End If
Next J

For i = 1 To 6
Lt(i) = Application.WorksheetFunction.Radians(.Cells(2 + i, 3))
Lg(i) = .Cells(2 + i, 4)
SM(i) = .Cells(2 + i, 5)
Next i

For i = 1 To 6
For h = 1 To 10
For J = 1 To 365
SoT(i, h, J) = CalcSoT(ST(h, J), ET(J), SM(i), Lg(i))
SAz(i, h, J) = CalcAs(DEC(J), Lt(i), SoT(i, h, J))
At(i, h, J) = CalcAt(Lt(i), DEC(J), SoT(i, h, J))
For k = 1 To 8
Az(k, i, h, J) = SAz(i, h, J) - Ae(k)
Ap(k, i, h, J) = CalcAp(At(i, h, J), Az(k, i, h, J))
Next k
Next J
Next h
Next i
.Cells(20, 20) = Ap(8, 1, 2, 305)
End With

'************************************************************************************
**********
i = 1
With Sheets("Phoenix")
Min = 90
For m = 1 To 12
For k = 1 To 8
    For h = 1 To 10
        For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
            If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) < Min Then
                Min = Ap(k, i, h, J)
                End If
                .Cells(1 + m, 2 + k) = Min
            End If
        Next J
    Next h
    Next k
Next m
End With

i = 2

With Sheets("Birmingham")
    Min = 90
    For m = 1 To 12
        For k = 1 To 8
            For h = 1 To 10
                For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) < Min Then
                        Min = Ap(k, i, h, J)
                        End If
                        .Cells(1 + m, 2 + k) = Min
                    End If
                Next J
            Next h
            Next k
        Next m
    End With

i = 3

With Sheets("Denver")
    Min = 90
    For m = 1 To 12
        For k = 1 To 8
            For h = 1 To 10
                For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) < Min Then
                        Min = Ap(k, i, h, J)
                        End If
                        .Cells(1 + m, 2 + k) = Min
                    End If
                Next J
            Next h
            Next k
        Next m
    End With

i = 4

With Sheets("Pittsburgh")
    Min = 90
    For m = 1 To 12
        For k = 1 To 8
            For h = 1 To 10
                For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) < Min Then
                        Min = Ap(k, i, h, J)
                        End If
                    End If
                Next J
            Next h
            Next k
        Next m
    End With
.Cells(l + m, 2 + k) = Min
Next J
Next h
Min = 90
Next k
Next m
End With

i = 5

With Sheets("Fargo")
Min = 90
For m = 1 To 12
For k = 1 To 8
For h = 1 To 10
For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) < Min Then
Min = Ap(k, i, h, J)
End If
.Cells(l + m, 2 + k) = Min
Next J
Next h
Min = 90
Next k
Next m
End With

i = 6

With Sheets("Seattle")
Min = 90
For m = 1 To 12
For k = 1 To 8
For h = 1 To 10
For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) < Min Then
Min = Ap(k, i, h, J)
End If
.Cells(l + m, 2 + k) = Min
Next J
Next h
Min = 90
Next k
Next m
End With
End Sub

B.2 Annual hours of profile angles are below the cut-off angles for each city (VBA)

'Subroutine to compute hours of accumulation
Sub Computeprofileangleshours()
Dim Lg(6) As Double
Dim Lt(6) As Double
Dim SM(6) As Double
Dim Jstart As Double
Dim Jend As Double
Dim ST(10, 365) As Double
Dim ET(365) As Double
Dim SoT(6, 10, 365) As Double
Dim DEC(365) As Double
Dim At(6, 10, 365) As Double
Dim SAz(6, 10, 365) As Double
Dim Ae(8) As Double
Dim Az(8, 6, 10, 365) As Double
Dim Ap(8, 6, 10, 365) As Double
Dim h As Integer                    ' 10 hours
Dim i As Integer                    ' 6 locations
Dim J As Integer                    ' 365 days
Dim k As Integer                    ' 8 elevation azimuths
Dim m As Integer                    ' 12 month
Dim non(8) As Integer               ' non-overhang
Dim one(8) As Integer               ' one ft
Dim two(8) As Integer               ' two ft
Dim thr(8) As Integer               ' three ft
Dim fou(8) As Integer               ' four ft
Dim fiv(8) As Integer
With Sheets("Input")
  Jstart = .Cells(11, 5)
  Jend = .Cells(12, 5)
  Ae(1) = 0
  Ae(2) = -Application.WorksheetFunction.PI() / 4
  Ae(3) = -Application.WorksheetFunction.PI() / 2
  Ae(4) = -Application.WorksheetFunction.PI() / 4 * 3
  Ae(5) = Application.WorksheetFunction.PI()
  Ae(6) = (Application.WorksheetFunction.PI() / 4 * 3)
  Ae(7) = (Application.WorksheetFunction.PI() / 2)
  Ae(8) = (Application.WorksheetFunction.PI() / 4)
  ET(J) = .Cells(J + 2, 13)
  DEC(J) = .Cells(J + 2, 14)
  If J >= Jstart And J < Jend Then
    For h = 1 To 10
      ST(h, J) = .Cells(2 + h, 10)
      Next h
    Else
      For h = 1 To 10
        ST(h, J) = .Cells(2 + h, 9)
        Next h
  End If
  For i = 1 To 6
    Lt(i) = Application.WorksheetFunction.Radians(.Cells(2 + i, 3))
    Lg(i) = .Cells(2 + i, 4)
    SM(i) = .Cells(2 + i, 5)
  Next i
  For i = 1 To 6
    For h = 1 To 10
      For J = 1 To 365
        SoT(i, h, J) = CalcSoT(ST(h, J), ET(J), SM(i), Lg(i))
        SAz(i, h, J) = CalcAs(DEC(J), Lt(i), SoT(i, h, J))
        At(i, h, J) = CalcAt(Lt(i), DEC(J), SoT(i, h, J))
        For k = 1 To 8
          Az(k, i, h, J) = SAz(i, h, J) - Ae(k)
          Ap(k, i, h, J) = CalcAp(At(i, h, J), Az(k, i, h, J))
        Next k
      Next J
    Next h
  Next i
.Cells(20, 20) = Ap(8, 1, 2, 305)
End With
i = 1
With Sheets("Phoenix")
    For k = 1 To 8
        non(k) = 0
        one(k) = 0
        two(k) = 0
        thr(k) = 0
        fou(k) = 0
        fiv(k) = 0
    Next k
    For k = 1 To 8
        For m = 1 To 12
            For h = 1 To 10
                For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
                        non(k) = non(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
                        one(k) = one(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 57.3 Then
                        two(k) = two(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 51.8 Then
                        thr(k) = thr(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 47.1 Then
                        fou(k) = fou(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 43# Then
                        fiv(k) = fiv(k) + 1
                    End If
                Next J
            Next h
        Next m
    .Cells(2, 2 + k) = non(k)
    .Cells(3, 2 + k) = one(k)
    .Cells(4, 2 + k) = two(k)
    .Cells(5, 2 + k) = thr(k)
    .Cells(6, 2 + k) = fou(k)
    .Cells(7, 2 + k) = fiv(k)
Next k
End With

i = 2
With Sheets("Birmingham")
    For k = 1 To 8
        non(k) = 0
        one(k) = 0
        two(k) = 0
        thr(k) = 0
        fou(k) = 0
        fiv(k) = 0
    Next k
For k = 1 To 8
For m = 1 To 12
For h = 1 To 10
For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
  If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
    non(k) = non(k) + 1
  End If
  If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
    one(k) = one(k) + 1
  End If
  If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 57.3 Then
    two(k) = two(k) + 1
  End If
  If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 51.8 Then
    thr(k) = thr(k) + 1
  End If
  If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 47.1 Then
    fou(k) = fou(k) + 1
  End If
  If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 43# Then
    fiv(k) = fiv(k) + 1
  End If
Next J
Next h
Next m
.Cells(2, 2 + k) = non(k)
.Cells(3, 2 + k) = one(k)
.Cells(4, 2 + k) = two(k)
.Cells(5, 2 + k) = thr(k)
.Cells(6, 2 + k) = fou(k)
.Cells(7, 2 + k) = fiv(k)
Next k
End With

i = 3
With Sheets("Denver")
  For k = 1 To 8
    non(k) = 0
    one(k) = 0
    two(k) = 0
    thr(k) = 0
    fou(k) = 0
    fiv(k) = 0
  Next k
  For k = 1 To 8
    For m = 1 To 12
      For h = 1 To 10
        For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
          If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
            non(k) = non(k) + 1
          End If
          If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
            one(k) = one(k) + 1
          End If
          If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 57.3 Then
            two(k) = two(k) + 1
          End If
          If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 51.8 Then
            thr(k) = thr(k) + 1
          End If
          If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 47.1 Then
            fou(k) = fou(k) + 1
          End If
          If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 43# Then
            fiv(k) = fiv(k) + 1
          End If
        Next J
      Next h
    Next m
  Next k
End With
If $A(t, i, h, J) > 0$ And $A(p, k, i, h, J) > 0$ And $A(p, k, i, h, J) \leq 47.1$ Then

\[ f(t) = f(t) + 1 \]

If $A(t, i, h, J) > 0$ And $A(p, k, i, h, J) > 0$ And $A(p, k, i, h, J) \leq 43$ Then

\[ f(i) = f(i) + 1 \]

End If

End If

End If

End If

End If

Next $J$

Next $h$

Next $m$

.Cells(2, 2 + $k$) = $n(t)$
.Cells(3, 2 + $k$) = $o(t)$
.Cells(4, 2 + $k$) = $t(t)$
.Cells(5, 2 + $k$) = $t(h)$
.Cells(6, 2 + $k$) = $f(t)$
.Cells(7, 2 + $k$) = $f(i)$

Next $k$

End With

$i = 4$

With Sheets("Pittsburgh")

For $k = 1$ To 8

$non(k) = 0$
$one(k) = 0$
		 two(k) = 0
	 thr(k) = 0
	 fou(k) = 0
	 fiv(k) = 0

Next $k$

For $k = 1$ To 8

For $m = 1$ To 12

For $h = 1$ To 10

For $J = .Cells(m, 11) + 1$ To .Cells(m + 1, 11)

If $A(t, i, h, J) > 0$ And $A(p, k, i, h, J) > 0$ And $A(p, k, i, h, J) \leq 63.4$ Then

\[ non(k) = non(k) + 1 \]

If $A(t, i, h, J) > 0$ And $A(p, k, i, h, J) > 0$ And $A(p, k, i, h, J) \leq 63.4$ Then

\[ one(k) = one(k) + 1 \]

If $A(t, i, h, J) > 0$ And $A(p, k, i, h, J) > 0$ And $A(p, k, i, h, J) \leq 57.3$ Then

\[ two(k) = two(k) + 1 \]

If $A(t, i, h, J) > 0$ And $A(p, k, i, h, J) > 0$ And $A(p, k, i, h, J) \leq 51.8$ Then

\[ thr(k) = thr(k) + 1 \]

If $A(t, i, h, J) > 0$ And $A(p, k, i, h, J) > 0$ And $A(p, k, i, h, J) \leq 47.1$ Then

\[ fou(k) = fou(k) + 1 \]

If $A(t, i, h, J) > 0$ And $A(p, k, i, h, J) > 0$ And $A(p, k, i, h, J) \leq 43$ Then

\[ fiv(k) = fiv(k) + 1 \]

End If

End If

End If

End If

Next $J$

Next $h$

Next $m$

.Cells(2, 2 + $k$) = $n(t)$
.Cells(3, 2 + $k$) = $o(t)$
i = 5

With Sheets("Fargo")
    For k = 1 To 8
        non(k) = 0
        one(k) = 0
        two(k) = 0
        thr(k) = 0
        fou(k) = 0
        fiv(k) = 0
    Next k
    For k = 1 To 8
        For m = 1 To 12
            For h = 1 To 10
                For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
                        non(k) = non(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
                        one(k) = one(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 57.3 Then
                        two(k) = two(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 51.8 Then
                        thr(k) = thr(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 47.1 Then
                        fou(k) = fou(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 43# Then
                        fiv(k) = fiv(k) + 1
                    End If
                Next J
            Next h
        Next m
    Next k
End With

i = 6

With Sheets("Seatle")
    For k = 1 To 8
        non(k) = 0
        one(k) = 0
        two(k) = 0
        thr(k) = 0
        fou(k) = 0
        fiv(k) = 0
    Next k
    For k = 1 To 8
        For m = 1 To 12
            For h = 1 To 10
                For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
                        non(k) = non(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
                        one(k) = one(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 57.3 Then
                        two(k) = two(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 51.8 Then
                        thr(k) = thr(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 47.1 Then
                        fou(k) = fou(k) + 1
                    End If
                    If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 43# Then
                        fiv(k) = fiv(k) + 1
                    End If
                Next J
            Next h
        Next m
    Next k
End With
fiv(k) = 0
Next k
For k = 1 To 8
    For m = 1 To 12
        For h = 1 To 10
            For J = .Cells(m, 11) + 1 To .Cells(m + 1, 11)
                If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
                    non(k) = non(k) + 1
                End If
                If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 63.4 Then
                    one(k) = one(k) + 1
                End If
                If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 57.3 Then
                    two(k) = two(k) + 1
                End If
                If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 51.8 Then
                    thr(k) = thr(k) + 1
                End If
                If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 47.1 Then
                    fou(k) = fou(k) + 1
                End If
                If At(i, h, J) > 0 And Ap(k, i, h, J) > 0 And Ap(k, i, h, J) <= 43.1 Then
                    fiv(k) = fiv(k) + 1
                End If
            Next J
        Next h
    Next m
    .Cells(2, 2 + k) = non(k)
    .Cells(3, 2 + k) = one(k)
    .Cells(4, 2 + k) = two(k)
    .Cells(5, 2 + k) = thr(k)
    .Cells(6, 2 + k) = fou(k)
    .Cells(7, 2 + k) = fiv(k)
Next k
End With
End Sub

B.3 Python scripts for extracting monthly data and new .ill data combination with sDA300/50%
calculation

```python
import os
import sys
import math
from collections import Counter

rule = [10]
angle = ['0', '045', '090', '135', '180', '225', '270', '315']
feet = ['0', '1', '2', '3', '4']
filerule = {1:'R0', 2:'R15', 3:'R30', 4:'R45', 5:'R60'}

def readCSV(filename):
    with open(filename, 'r', encoding = "utf-8") as fp:
        count = 0
        for lines in fp:
            line = lines[0]
            if not count:
                rule[line.split(',')[0]] = {}
                mark = line.split(',')[0]
            else:
```

temp = {}
templist = line.split(',
for x in range(1, len(templist)):
temp[angle[x - 1]] = templist[x]
rule[mark][count] = temp
if count == 12:
count = 0
else:
count += 1

def main(argv):
    readCSV('./CR.csv')
    length = 0
    # print(rule)
    for city in rule:
        for foot in feet:
            for ang in angle:
                filenamePrefix = 'D:' + city + ang + 'ft'
                counter_light = Counter()
                out_file = open(filenamePrefix + 'ft_merge.txt','w')
                for index in filerule:
                    file_to_process = filenamePrefix + 'ft_' + filerule[index] + '.txt'
                    file_operation = open(file_to_process,'r')
                    for lines in file_operation:
                        lines = lines[0] + 'n'
                        month = lines.split(' ')[0]
                        length = len(lines.split(' ')) - 4
                        # print(rule[city][int(month)][ang])
                        if rule[city][int(month)][ang] != filerule[index]:
                            continue
                        points = lines.split(' ')
                        if int(month) < 3 or int(month) > 10:
                            if float(points[2]) < 8.5 or float(points[2]) > 17.5:
                                continue
                            else:
                                out_file.write(lines + 'n')
                                for x in range(3, len(points) - 1):
                                    if int(points[x]) > 300:
                                        counter_light[x - 3] += 1
                                else:
                                    if float(points[2]) < 7.5 or float(points[2]) > 16.5:
                                        continue
                                    else:
                                        out_file.write(lines + 'n')
                                        for x in range(3, len(points) - 1):
                                            if int(points[x]) > 300:
                                                counter_light[x - 3] += 1
                        # calculate ratio
                        hit = 0
                        for x in counter_light:
                            if counter_light[x] > 1825:
                                hit += 1
                        print(filenamePrefix)
                        print(hit / length)

if __name__ == '__main__':
    main(sys.argv[1:])
The matrix plot of the shade options in the analysis period all year round (Matlab script)

clc;clear;close all;
[a,b]=uigetfile('*.txt')
filename=[b,a];
sho=importdata(list.txt);
for i=1:365
  if i<67 | i > 305
    dat(:,i)=sho(i*24-23:i*24)
  else
    dat(:,i)=sho(i*24-24:i*24-1)
  end
end
pcolor(dat(8:18,:))
set(gca,'XTick',
    [15 45 75 105 135 165 195 225 255 285 315 345],...
    'XTickLabel',...
    {'Jan','Feb','Mar','Apr','May','Jun','Jul','Aug','Sep','Oct','Nov','Dec'},...
    'YTick',[1 2 3 4 5 6 7 8 9 10 11],...
    'YTickLabel',...
    {'8 AM','9 AM','10 AM','11 AM','12 PM','1 PM','2 PM','3 PM','4 PM','5 PM','6 PM'});
set(gca,'plotboxaspectratio',[4 1 1]);

a(1:5)=[]
a=strrep(a,'0.txt','S(0 Deg)');
a=strrep(a,'045.txt','SE(45 Deg)');
a=strrep(a,'090.txt','E(90 Deg)');
a=strrep(a,'080.txt','NE(135 Deg)');
a=strrep(a,'180.txt','N(180 Deg)');
a=strrep(a,'225.txt','NW(225 Deg)');
a=strrep(a,'315.txt','W(315 Deg)');

b(1:18)=[];
b=strrep(b,'ft\','ft overhang with windows facing ');
b=strrep(b,'_','');

print(gcf,'-deps', tt);