

Development of Annual Daylight Performance Metrics: Sensitivity Analyses of Illuminance
Thresholds and Blind Use, and Examinations of Energy Use Implications

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AUTHORIZATION TO SUBMIT THESIS

This thesis of Amir Nezamdoost, submitted for the degree of Master of Science with a major in Integrated Architecture and Design and titled “Development of Annual Daylight Performance Metrics: Sensitivity Analyses of Illuminance Thresholds and Blind Use, and Examinations of Energy Use Implications,” has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

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ABSTRACT

With the latest published version LEED (v4), and the IES codifying two recommended annual-climate-based daylighting metrics and performance criteria, annual daylighting simulation has become even more important to the design professions than ever before. However, interpretation and application of annual-climate-based daylighting data are still relatively novel. Moreover, there remains a lack of consensus regarding the proper behavioral patterns that annual-climate-based daylighting simulation should employ regarding operation of interior manually-controlled window blinds. This study documents a 8-year human factors daylighting field research project using students' daylit area drawings and qualitative assessments of daylight sufficiency and corresponding point-in-time and annual-climate-based daylighting simulation in a variety of building types (n=24) in order to provide insight to the building performance simulation community about application of these new annual daylighting metrics. Additionally, three candidate manual blind control algorithms (Blindswitch 2012-A, Blindswitch 2012-B, and LM-83) were tested in order to provide insight into the role of manual blind use and the relationship to students' evaluations to annual simulation results.

ACKNOWLEDGEMENTS

Though only my name appears on the cover of this thesis, a great many people have contributed to its production. I owe my gratitude to all those people who have made this thesis possible and because of whom my graduate experience has been one that I will cherish forever.

My deepest gratitude is to my advisor, Dr. Kevin Van Den Wymelenberg. I have been amazingly fortunate to have an advisor who gave me the freedom to explore on my own and at the same time the guidance to recover when my steps faltered. Kevin taught me how to question thoughts and express ideas. His patience and support helped me overcome many crisis situations and finish this thesis.

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Most importantly, none of this would have been possible without the love and patience of my family. I owe more than thanks to my kind parents, lovely sisters (Nazi, Nooshin and Nadia), and warm-hearted wife.

DEDICATION

My humble effort I dedicate to my kind-hearted and loving

Father & Mother,

Whose affection, love, encouragement and prayers of day and night

make me able to get such success and honor,

And

To my brilliant wife,

Malaknaz,

Whose unyielding love, support and encouragement have enriched

my soul and inspired me to pursue this work.

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CHAPTER 1

Daylit Area Revisited: A Comparative Sensitivity Study of Daylit Area Drawings with Daylight Results from Point-in-Time and Annual Simulations

With the Illuminating Engineering Society (IES) recently adopting Lighting Measurement #83 (LM-83), and codifying two recommended annual-climate-based daylighting metrics and performance criteria, annual daylighting simulation has become even more important to the design professions, reach standard and energy code organizations. The benefits of daylighting are well established. However, interpretation and application of annual-climate-based daylighting data are still relatively novel. Furthermore, the details about how building inhabitants engage with daylighting controls in spaces with daylight over time (relative to annual simulation) is less known. There remains a lack of consensus regarding the proper behavioral patterns that annual-climate-based daylighting simulation should employ regarding operation of interior manually-controlled window blinds. Secondary validation studies of these new annual daylighting metrics and criteria are needed in order to increase designers' confidence in their use and to help improve the science of annual-climate-based daylight simulation in the future. This paper documents human factors daylighting field study research using student "daylit area" drawings and corresponding point-in-time and annual-climate-based daylighting simulation with alternate blind control algorithms employed in order to provide insight to the building performance simulation community about the use and application of these new annual daylighting metrics.

Results indicate that point-in-time simulation results with blinds retracted showed less discrepancy between student daylit area evaluations than did annual simulation results regardless of the blind operation algorithm used. Still, the better understanding of annual-climate-based daylighting metrics is essential. Therefore, substantial analysis is presented about both point-in-time and annual simulation results. The paper also identifies and explains inconsistencies between alternate annual blind control algorithms with regard to determination of spaces as "nominally daylit" or having "preferred daylight" according to LM-83 terminology. For point-in-time analyses, student evaluations conducted under clear skies and in study spaces with only vertical

fenestration showed greater discrepancy with simulated results for the “non-daylit” and “partially daylit” designations than those conducted under overcast skies and those in study spaces with toplighting. On the other hand, student evaluations conducted under overcast skies and in study spaces with only vertical fenestration showed greater discrepancy with simulated results for the “fully daylit” designation. Student evaluations and point-in-time simulation results were more similar in spaces with some toplighting component than those having only sidelighting regardless of sky condition.

There were statistically significant differences regarding the most representative horizontal illuminance indicator value for discerning between “non-”, “partially” and “fully” daylit areas. Interestingly, for “fully daylit” areas, the illuminance indicator value, 250 Lux, consistently emerged across sky conditions and daylight aperture types as having the least discrepancy with daylit area drawings. It was found that a moderating variable defined by the authors as “Occupant Brightness Perception” had a statistically significant ($p < 0.00075$) impact on student evaluations of daylit areas in rooms with generally higher illuminance levels whereby students considered spaces to be better daylit in cases where walls opposite perimeter vertical fenestration were washed with daylight. The t-test suggests statistical significance, the sample of spaces with this condition is small and therefore, this should be considered a preliminary finding.

The following horizontal illuminance thresholds emerged from the sensitivity analysis as representing consistently low discrepancy between student evaluations and point-in-time simulation results; the threshold between “non-daylit” and “partially daylit” produced 100 Lux and the threshold between “partially daylit” and “fully daylit” produced 250 Lux. These are slightly lower than previously published indicator values (150, 300 lux). This is possibly due to the relatively young sample of human participants in this study. Other thresholds could be argued as having the least discrepancy for certain conditions (sky condition, daylight aperture type). However, based on this study, these values (100, 250 Lux) are recommended for future use in annual-climate-based daylighting analysis because they are logical and represent consistently low error across multiples space types, times of year, aperture types and sky conditions.

1. Introduction

A daylit space is primarily lit with natural light and combines high occupant satisfaction with the visual and thermal environment with low overall energy use for lighting, heating and cooling (Reinhart 2011).

The importance of occupant satisfaction in spaces with daylight is undeniable based upon several daylighting studies (Marans and Yan, 1989; Roche et al. 2000; Galasiu and Veitch, 2006; Veitch et al., 2007; Van Den Wymelenberg et al., 2010; Choi et al., 2011; Heschong and Van Den Wymelenberg, 2012; Konis 2013; Borisuit et al., 2015). Benefits related to occupant comfort, satisfaction and well-being in daylit spaces such as offices and classrooms can be substantial (Leslie 2003, Heschong 2003) and several codes and standard organizations have begun to promote annual daylight simulation to support improved design (IES Daylight Metrics Committee 2012, USGBC LEED V4). Because most buildings have manual blind use, and annual energy and daylighting simulation needs to consider this impact somehow, there has been much debate over the appropriate manual blind control assumptions that should be included in these simulations.

In recent years, manual and automated blind use patterns have been explored to understand their impact on occupant comfort and annual energy use in buildings (Newsham, 1994; Reinhart, 2004; Bourgeois, Reinhart, & Macdonald, 2006; da Silva, Leal, & Andersen, 2012; Van Den Wymelenberg, 2012; Dyke, et. al, 2015;; Nezamdoost et al. 2014). It is difficult to ignore the acceleration of interest among codes and standards organizations, manufacturers and even owners regarding the energy and human comfort impacts and advantages of manual and automated blinds in buildings. Unfortunately, the lack of a

universally recognized manual blind operation pattern has hampered progress toward the desired outcomes of these interested parties (Van Den Wymelenberg, 2012).

A suite of alternative manual blind patterns have been proposed (Blindswitch-2012 A and Blindswitch-2012 B and the algorithm used by LM-83 (Dyke et al. 2015 and IES Daylight Metrics Committee 2012). Research suggests that the alternate blind control algorithms result in meaningful differences by way of annual energy consumption and energy end use splits (heating, cooling, and lighting). It is reported that annual lighting end-use energy consumption of three strategies differed by approximately 6.6%, 3.7% and 2.2% using Blindswitch-A, -B and LM-83 respectively as compared to a baseline with blinds always retracted with daylight sensing lighting controls. For the same baseline, heating end-use consumption differed by 19.5%, 1.4% and 13.9% using Blindswitch-A, -B and LM-83 respectively (Nezamdoost et al. 2014). However, there has been very little data available to determine which of the candidate manual blind use pattern(s) should be used as a best practice in simulation, which produces annual daylight results that best correlate with occupant ratings of daylit performance, and how each impact determination of spaces as “nominally daylit” or having “preferred daylight” according to LM-83 terminology. Additionally, there are few human factors daylighting studies available to examine the relationship between point-in-time and annual simulation results and human evaluations. While this paper does not definitively answer all of these questions, it makes substantial contributions to several areas of inquiry.

2. Methods

The research plan was designed to address one primary objective and several secondary objectives. The paper’s primary objective is to compare simulated daylight results with daylit area boundary drawings conducted by students of architecture to determine what

simulated parameters most closely corresponded with student qualitative assessments of “non-daylight”, “partially daylit” and “fully daylit” areas within study spaces. This follows up and builds upon two recent papers in this area (Reinhart et. al 2012 and Reinhart et al. 2014). The secondary objectives were to determine whether point-in-time or annual simulations more closely matched students’ perceptions of daylight sufficiency, which illuminance thresholds provide the greatest predictive ability for “partially” and “fully” daylit spaces, what the implications of alternate manual blind control patterns are in annual daylight simulations, and to contribute to the ongoing discussion of the limits and strengths of current annual-climate-based daylight metrics and the candidate manual blind control algorithms. Specifically, an examination of whether each study space met the requirements of LEED V4 EQ Daylight Credit. These secondary objectives were not explicitly explored in previous publications.

A substantial human factors field study was organized in 22 real spaces where graduate architecture students (ages <30 years) evaluated the spaces and documented the daylit area and non-daylit area using plan drawings. Studies were conducted over a period of three years (2012-2015) in Boise, ID and Seattle, WA in three space types (classroom, office, other), comprising 260 individual “daylit area” occupant evaluations. Daylight simulations were conducted using both annual and closely equivalent point-in-time simulation settings for comparative purposes. Annual simulations were run with alternate blind operation settings and point-in-time simulations were conducted both with blinds open and with blinds closed. Sensitivity studies for point-in-time simulations were conducted to see which illuminance indicator thresholds (ranging from 50-450 Lux) produced the smallest difference when comparing students’ assessments of fully daylit, partially daylit, and non-daylit areas within the study spaces.

2.1 Field Study

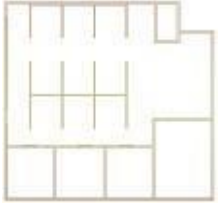
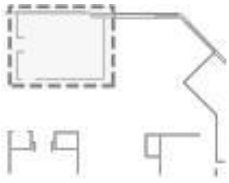
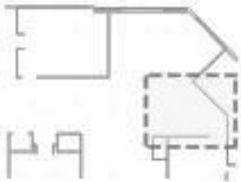


In order that this data set may contribute to current research (Heschong and Van Den Wymelenberg, 2012) and address several real world buildings that commonly aim to include daylight, a field study of three common space types was conducted. A general classification of space types is documented below while Table 1-1 and Figure 1-1 document several characteristics for each study space.

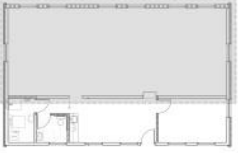
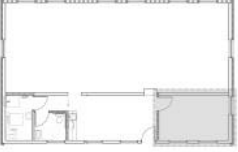


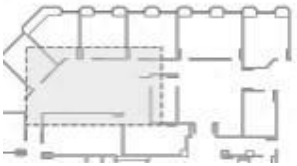

- (1) **Office space type (n=11):** In this space type, there are generally fixed desk locations with fixed viewing orientations for regular occupants who primarily work with computer, phone, and paper based tasks and communicate one-on-one. In this category, the authors' general concentration was on open offices (n=10) rather than private ones (n=1).
- (2) **Classroom space type (n=5):** In this space type several different tasks commonly occur (desk work, small group discussions, viewing the teaching wall) requiring multiple viewing orientations but typically with a single dominant viewing direction (toward the teaching wall).

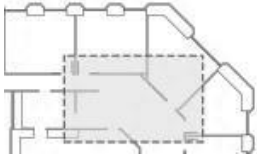
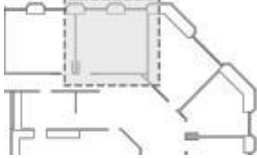


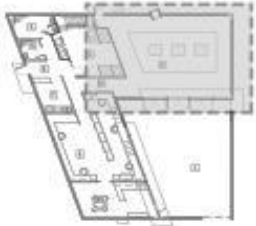
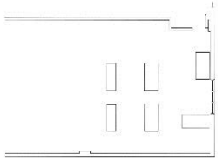
Conference rooms, meeting rooms and typical classrooms were categorized into this space type.

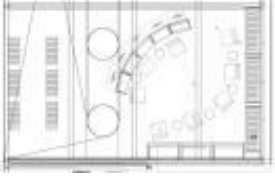
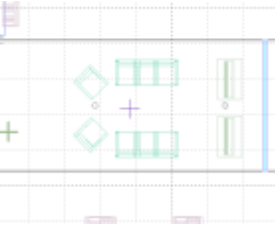

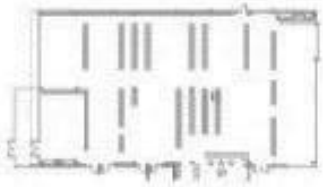
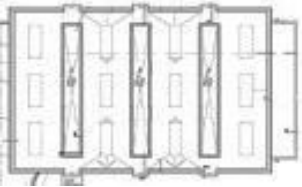
- (3) **Other space type (n=6):** These spaces potentially have more visitors than regular users. Occupants have the ability to move through and around the space. They can choose to work in their favorite location or may just be passing through. Spaces such as libraries, galleries, gymnasiums and lobbies were categorized into this space type.

Table 1-1 Overview of Study Spaces

Building	Space Type	# Student Evals.	Sky	Dates of Eval.	Type of Blinds
# 001 Boise, ID 	Open Office	11	Clear	2/12/2012	Horizontal 2-inch white louver blinds
# 002 Boise, ID 	Open Office	12	Clear	4/10/2012	No blinds; with overhang
# 003 Boise, ID 	Reception	12	Clear	4/10/2012	No blinds
# 004 Boise, ID 	Classroom	12	Partly Cloudy	3/27/2012	No blinds; with overhang
# 005 Boise, ID 	Office	12	Overcast	3/27/2012	No blinds; with overhang

<p># 006 Boise, ID</p> 	Open Office	12	Overcast	3/20/2012	No blinds, fixed overhang on south facade
<p># 007 Boise, ID</p> 	Conference Room	12	Overcast	3/20/2012	No blinds
<p># 008 Boise, ID</p> 	Classroom	12	Overcast	1/24/2012	Horizontal white louver blinds
		12	Partly Cloudy	4/17/2012	
		10	Overcast	2/11/2014	
<p># 009 Boise, ID</p> 	Open Office	12	Overcast	1/24/2012	Horizontal white louver blinds + Roller shade
		12	Partly Cloudy	4/17/2012	
		10	Overcast	2/11/2014	
<p># 010 Boise, ID</p> 	Open Office	12	Overcast	4/3/2012	Horizontal white louver blinds
<p># 011 Boise, ID</p> 	Conference Room	12	Overcast	4/3/2012	Horizontal white louver blinds

<p># 012 Boise, ID</p> 	Open Office	12	Overcast	4/3/2012	Horizontal white louver blinds
<p># 013 Boise, ID</p> 	Private Office	12	Overcast	4/3/2012	Horizontal louver blinds
<p># 014 Boise, ID</p> 	Open office	-	Clear	8/31/2010	Roller fabric shades
<p># 015 Boise, ID</p> 	Studio	10	Partly Cloudy	2/4/2014	Roller fabric shades
<p># 016 Boise, ID</p> 	Gallery	-	Clear	9/21/2010	Curtain sheers
<p># 017 Boise, ID</p> 	Open Office	12	Overcast	1/24/2012	No blinds

<p># 018 Seattle, WA</p> 	Periodical Reading Room	-	Overcast	9/17/2007	Horizontal louver blinds on clerestory openings
<p># 019 Seattle, WA</p> 	Stacks Reading Room	-	Overcast	9/17/2007	Horizontal louver blinds on clerestory openings
<p># 020 Seattle, WA</p> 	2nd Floor - North Open Office	6	Overcast	2/17/2012	South: exterior motorized blinds; North/East/West: Horizontal white louver blinds
<p># 021 Boise, ID</p> 	Library	10	Clear	3/4/2014	Roller fabric shades on south facade
<p># 022 Seattle, WA</p> 	Gym	7	Overcast	2/17/2012	No blinds

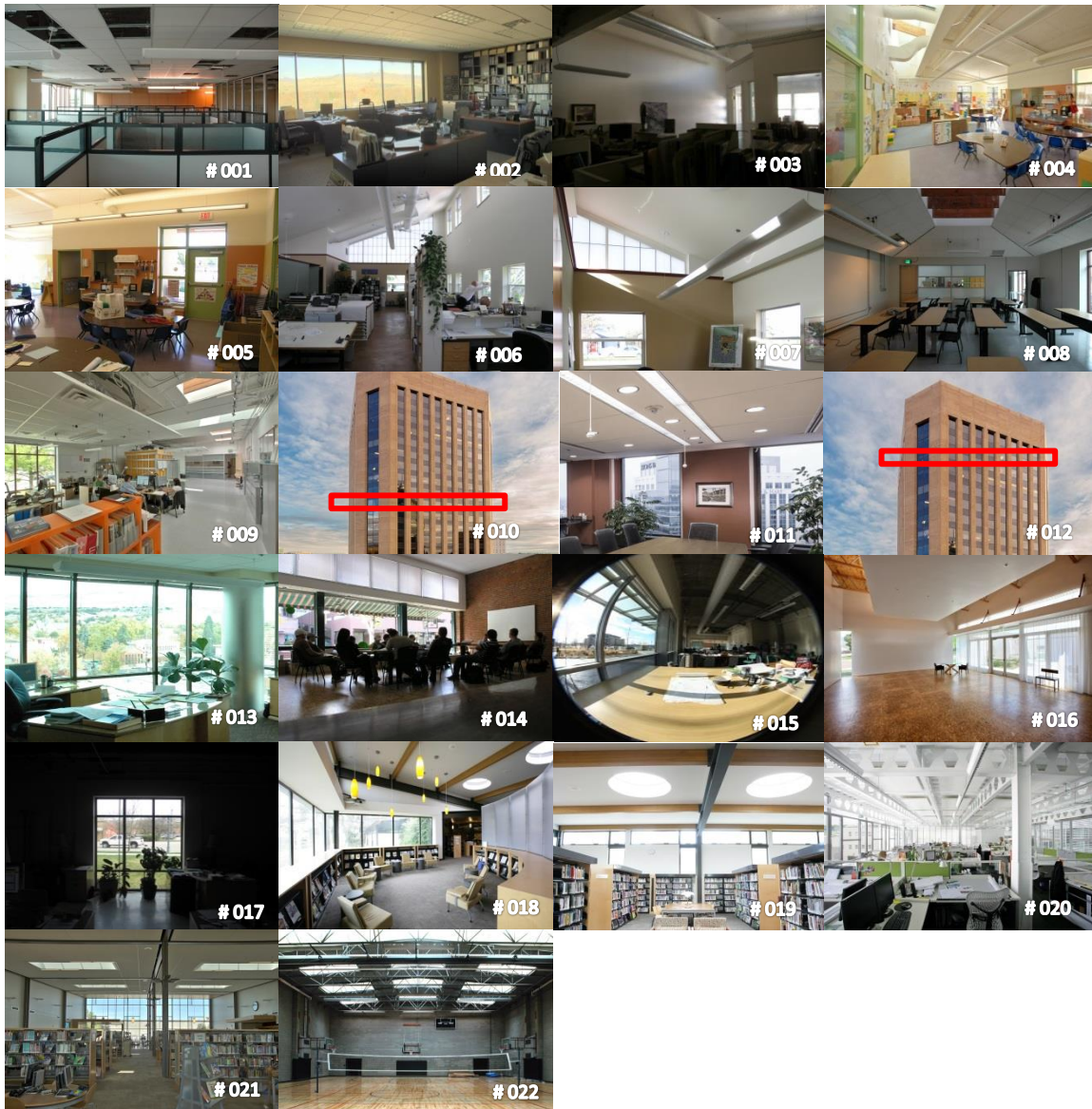


Figure 1-1 Photos of study spaces

2.2 Experimental Setup

From January 2012 – May 2015 the second author taught a graduate level seminar to architectural students at the University of Idaho in Boise titled Daylighting Design and Simulation where the field study was conducted over several field trips. At the beginning of each field trip, after students had spent several minutes in the room experiencing it from

multiple points of view and understanding the functional purpose of the space, students were given the following instruction:

“In this exercise you are asked to follow your own intuition and divide the designated study area into a daylit and a non daylit area. Within the daylit area indoor illuminances levels due to natural light should be adequate, useful and balanced for most of the year. Please conduct your assessment individually without consulting with other students.”

After that, students conducted illuminance measurements and completed a three-page questionnaire (results reported elsewhere). Whenever possible, evaluations were conducted with all electric lights off and any movable shading systems fully retracted (opened). In those spaces that had automated shading systems ($n = 2$), the blinds remained in the automatically controlled position. Figure 1-2 shows one of the field trip locations with students conducting their evaluation. The research protocol (project 15-724) was reviewed by the Institutional Review Board at the University of Idaho and was certified as exempt.



Figure 1-2 Students' Field Trip

2.3 Daylit Drawings Evaluation

All paper-based daylit area evaluations completed during the three-year period were gathered, digitally scanned, and translated to vector line drawings in AutoCAD (Figure 2-3-left). As expected, the boundary areas drawn by each student varied substantially and the authors employed an “area-based averaging function” following previous similar research. “The daylit and partially daylit areas within a space respectively correspond to areas for

which either the majority (>75%) or a sizable portion (>25%) of occupants voted (drew) that the area within the space was daylit, while the remaining area is ‘non daylit’” (Reinhart et. al, 2014). An area in a space was coded as “fully daylit” whenever 75% or more of the evaluations designated it as a daylit area. The areas that were designated by 25%-74% of the evaluations to be daylit were coded as “partially daylit” areas. If fewer than 25% of the evaluations designated an area as daylit, that area was coded as a “non-daylit” area. Figure 1-3-right shows the results for space #008.

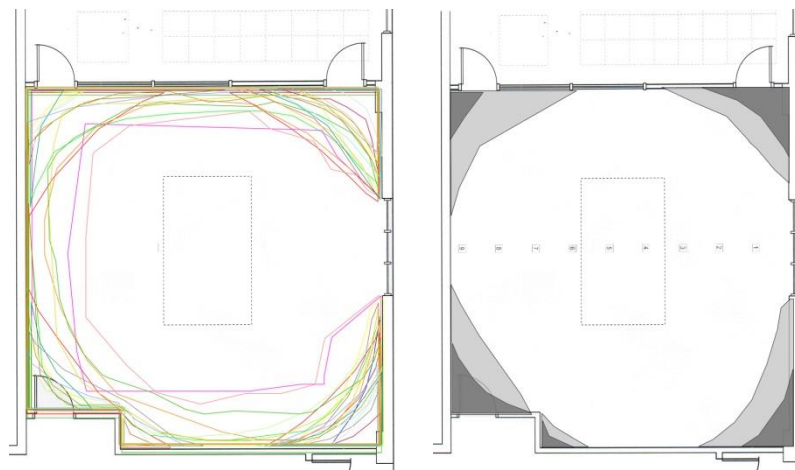


Figure 1-3 Area Based Averaging Function- Space #008

Left: Overlaid daylight boundary drawings of all students
 Right: Resulting “fully” (white), “partially” (grey), and “non-daylit” areas (black)

2.4 Simulation Parameters

In order to make comparisons between results from simulation and those from the student daylit area evaluations, accurate 3D geometry models are essential. Detailed digital interior models of all spaces and relevant massing of surrounding buildings and site context were generated in SketchUp. The simulation protocol outlined in LM-83 (IESNA-Daylight Metrics Committee 2012) was used unless noted otherwise. This protocol requires substantial detail to be included in the digital models. When the models were complete and verified for

accuracy against floor plans, photographs and Google Earth; they were exported to the RADIANCE daylight simulation engine. Per LM-83, an illuminance analysis grid of 2'x2' was used for generating illuminance point data.

For point-in-time simulations, the authors began with 150 and 300 lux illuminance thresholds as proposed by Reinhart et al. (2014) (although this was for their annual analyses) to define boundaries of “non”(below 150 lux), “partial” (150-299 lux) and “fully” daylit areas (above 300 lux). Additionally, the authors examined sensitivity analysis on alternate point-in-time illuminance thresholds to find the most accurate match with students’ daylit area drawings. For the point-in-time comparisons between simulations and daylit area drawings, a simulation data set was selected with the same clock time, from the same week and with a matching sky condition from the annual simulation results (discussed below) to provide a very similar basis of comparison as to when the students conducted the evaluations in the field.

For annual climate-based daylight simulation, the three-phase method was employed (McNeil and Lee, 2013), per LM-83(IESNA-Daylight Metrics Committee 2012). *Rcontrib* ambient calculations were used in RADIANCE to compute light source contributions. Materials and shades were assigned to digital models based on the materials in actual spaces using CIBSE surfaces and reflectance charts and bidirectional scattering distribution function (BSDF). One substantial progression of this paper from the previous daylit area studies is that manual dynamic blind algorithms are tested. Below, in Table 1-2, a list of the RADIANCE simulations parameters for all study spaces are documented.

Table 1-2 RADIANCE Simulation Parameters

Ambient bounces	Ambient division	Ambient sampling	Ambient accuracy	Ambient resolution	Direct threshold
6	4096	1024	0.1	256	0

Similar to the students' paper-based evaluations, the authors determined a need to define a "partially daylit" area based upon the annual simulation results. Therefore, two levels of annual daylight sufficiency performance criteria based upon the metric *spatial Daylight Autonomy (sDA)* (IESNA-Daylight Metrics Committee 2012 and Hescong & Van Den Wymelenberg 2012) were used. Similar to the point-in-time analyses, fully daylit areas were designated as those having 300 lux for at least 50% of the occupied hours (8AM-6PM) and partially daylit areas had between 150-299 Lux for at least 50% of the time. Figure 1-4 demonstrates the simulation-based analysis in one example study space showing the fully, partially and non-daylit areas.

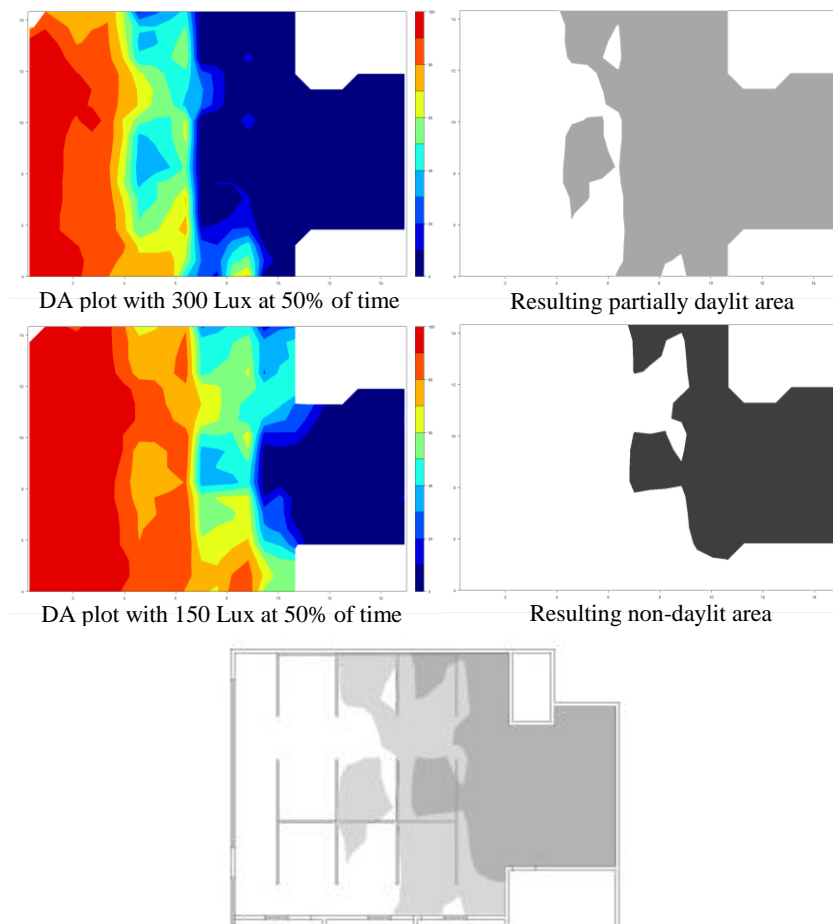


Figure 1-4 Simulation Based Analysis

Left: Standard daylight autonomy plots with 150 and 300 Lux at 50% of time basis with windows always retracted
 Right: Resulting "fully" (white), "partially" (grey), and "non-daylit" areas (dark grey)

2.5 Simulating Dynamic Manually Operated Blinds

Blindswitch-A and –B were proposed for use with whole building simulations (or larger areas that could logically be divided into ten window groups), whereas LM-83 uses a space-by-space approach for both daylight performance characterization and hourly blind control, and therefore applies most directly to smaller defined spaces. In order to establish a relevant basis of comparison of the algorithms, some rules and refinements were required and are outlined below.

According to IES LM-83 2012 documentation (section 2.2.6 Blinds/Shades Operation): “...All exterior windows must be modeled with blinds unless: Blinds will not be installed according to design documents, and the Annual Sunlight Exposure calculation for the analysis area associated with the window group meets or exceeds the recommended criteria for “nominally acceptable” occupant. Given that this paper documents already built structures, the authors decided to model only those exterior windows that already had blinds installed in reality as having blinds operated in the annual simulations.

Based on LM-83 documentation, it is permitted to divide windows into as many “window groups” for blind control as desired by the simulationist. However, the Blindswitch-A and –B algorithms were proposed with precisely ten window groups on each facade: two groups set as always retracted, two set as always engaged and six set as operable based upon the specifics of the algorithm. To reconcile this for spaces with only one or just a few windows, and no logical way to subdivide the window or windows into ten “window groups” for blind control, the following rule was developed. For those spaces having fewer than 10 logical window groups, an approximate scaling with some randomization of the ten possible window group definitions from each (Blindswitch-A and –B) algorithm were applied. If there

was only one window in the space, it was considered as operable window group number five for Blindswitch-A and –B. If there were two windows in a space, operable window groups number four and six were randomly applied to each window blind. For three windows in a space, the group numbers three, five and seven were randomly applied to the window blinds. If between four and nine logical window groups existed, the scenario of three windows was repeated plus one additional window group was randomly assigned for each additional logical window group in the building or space, as illustrated in Table 1-3.

Table 1-3 Procedure of Assigning Window Groups for Blindswitch-A&-B

Blue: Assigned to an available window group – Yellow: randomly applied to available window groups

10										
9										
8										
7										
6										
5										
4										
3										
2										
1										
# window groups	1	2	3	4	5	6	7	8	9	10
	Always Closed		Operable window groups						Always Open	

2.5.1 Overhangs - Blindswitch A

To model the control algorithm and generally get the blind schedules’ results in both Blindswitch-A and –B, the Energy Management System (EMS) within EnergyPlus were used. For Blindswitch-A in order to calculate penetration depth, the solar horizontal profile angle is used (Dyke et al. 2015).

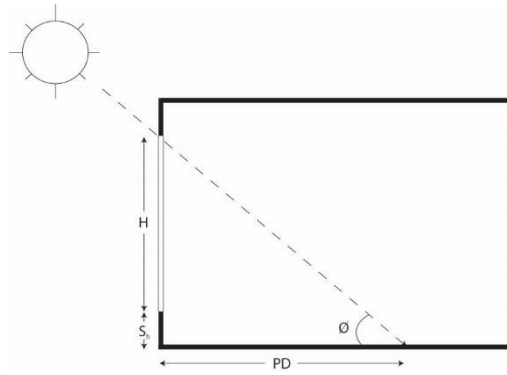


Figure 1-5 Penetration Depth

Equation 1-1 was used to calculate penetration depth (PD). H is window height (m), S_h is the sill height (m), and $HPA = \phi$ is the solar horizontal profile angle.

$$PD = \frac{(H + S_h)}{\tan(HPA)} \quad (1-1)$$

For those buildings with overhang or light shelf, the penetration depth decreases based on the width of overhangs/lightshelf and the incident angle (sun position).

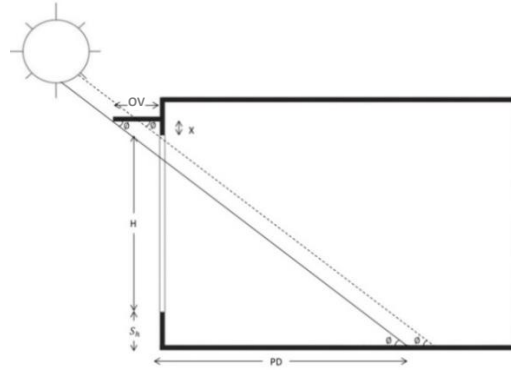


Figure 1-6 Penetration Depth in Spaces with Overhangs

Equation 1-2 was proposed to calculate sun penetration depth in a space with overhang only. Set OV to overhang depth, X to overhang height from top of the window and A to distance of overhang from window head. AL is altitude angle (angular distance above the horizon) and VPA is the solar vertical profile angle.

$$PD = \frac{(X + H + S_h) - \max\left\{\left(\frac{OV * \tan AL}{\cos(VPA)}\right), A\right\}}{\tan(HPA)} \quad (1-2)$$

For those spaces with both overhang and light shelf, equation 1-2 should be used for bottom window groups (overhangs) and equation 1-3 for top windows (light shelf).

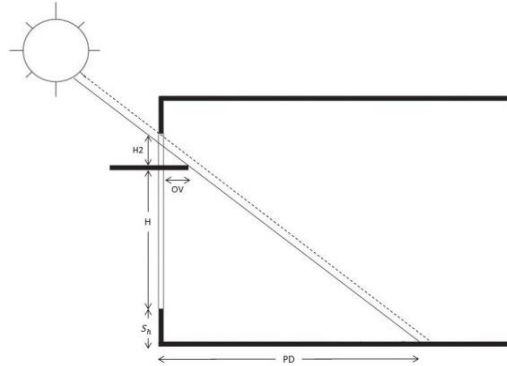


Figure 1-7 Penetration Depth in Spaces with Interior Light shelf

Equation 1-3 represents sun penetration depth calculation in a space with light shelf only. In this equation X2 is top window height.

$$PD = \frac{(X2 + H + S_h) - \max\left\{\left(\frac{OV * \tan AL}{\cos(VPA)}\right), A\right\}}{\tan(HPA)} \quad (1-3)$$

2.5.2 Rule Z for angled glasses

Because of how the *Rcontrib* ambient calculation method in RADIANCE is paired with the blind control algorithm in LM-83 (perspective view to projection view), the authors simulated any angled or non-orthogonal windows by dividing the window into two orthogonal windows as illustrated in Figure 1-8. In this example the window facing to the northeast was changed to two windows opposing each other by 90 degrees, one facing north and one facing east. This rule was required only for 4 spaces, specifically spaces #003, #010, #012 and #020.

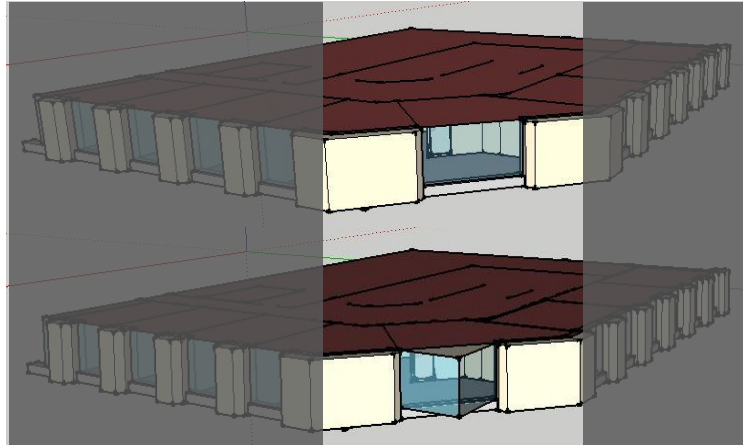


Figure 1-8 Rule Z- Angled Windows Simulation

3. Results

3.1 Comparing daylight availability plots

Table 1-4 illustrates and compares the fully daylit (white), partially daylit (light gray) and non-daylit (dark gray) areas in all 22 study spaces based on (1) students' daylight evaluations during field trips in the three-year period (2) simulated daylight availability in the exact time of student's evaluation (3) simulated annual daylight availability based on Blindswitch-A interior manual blind control pattern (4) simulated annual daylight availability based on Blindswitch-B interior manual blind control pattern (5) simulated annual daylight availability based on LM-83 manual blind control pattern (6) simulated annual daylight availability if blinds were always open and (7) simulated annual daylight availability if blinds were always closed. Table 1-4 is organized with spaces having blinds of some type appearing first and spaces without blinds appearing last.

Table 1-4 routinely reveals noticeable differences in the size and shape of the non-, partially, and fully daylit areas between the students' daylight area drawings relative to simulated annual daylight performance results. On the other hand, Table 1-4 also shows

reasonable similarity between the students' daylight area drawings and the point-in-time simulation results for 16 out of 22 study spaces (all except #004, #005, #010-014). It is interesting to note some features of the six spaces where the students' drawings noticeably do not align with the point-in-time simulation results.

Spaces #010 and #012 are located in the core of a building with a couple of interior relight windows and no direct daylight available. The simulations suggest the spaces are non-daylit, but the students found substantial fully daylight area across the whole length of space with some partial and non-daylit areas adjacent to the relight windows. In spaces #011 and #013, the students' evaluations suggest that the spaces are fully daylight with some partially daylight areas adjacent to the window openings while the simulations predict the first two thirds of the space (next to the windows) is daylight and the last third (far from window) is partially daylight. The results for spaces #011 and #013 suggest an interesting example of how the nature of human visual perception for daylight is complicated. Students found substantial daylight areas in a relatively dark space and this could be due to the dark adaptation. The human eye has different responses as a function of wavelength when it is adapted to light conditions (photopic vision) and very dark conditions (scotopic vision) (Michael Bass (ed.), 1995).

The two remaining unique spaces (#004 and #005) have clerestory openings facing to the south and north respectively in order to bring more natural light into the space. South-facing clerestory windows provide toplighting to the space. Light is directed onto an interior wall facing the clerestory openings. The bright wall may indicate to the students that the space is "brighter" than it is when considering only horizontal illuminance, and consequently caused students to evaluate the entire area as daylight. These two spaces, in conjunction with #010-014

begin to support a hypothesis about perception of brightness as a moderating variable that is elaborated in the discussion section.

As it was mentioned in methods section, in Table 1-4, in those spaces with no blinds installed, blind study was not conducted - there is no calculation of sDA value for blind algorithms in eight spaces (#002, #003, #004, #005, #006, #007, #017 and #022) and therefore plots are only shown in always open iteration. In those study spaces with no blinds, other strategies were used to control amount of sunlight such as exterior shading devices (Space #002, #004, #005 and #006). Accordingly, the *Annual Sunlight Exposure (ASE)* metric (IESNA-Daylight Metrics Committee 2012) was calculated for each space separately and shown in Table 1-4. Annual sunlight exposure (ASE) was recorded zero for a few spaces, which is not a big surprise. Spaces #003, #010 and #012 are located in the core zone of the buildings and no direct sun enters those spaces throughout the year. Spaces #002, #011 and #013 face to the north, have low VLT for windows, and use overhangs resulting in zero sunlight exposure during the occupied period (8AM- 6PM) during the year. For spaces #019 and #022, all the openings are translucent and no direct sunlight can hit the sensors.




	# 001 ASE=10.33 	# 008 ASE=2.59 	# 009 ASE=2.08 
Type of Blind	Louver Blind	Louver Blind	Louver Blind + Roller Shade
Students' Evaluation			
Point-in-time simulation			
Blindswitch-A Plot			
Blindswitch-B Plot			
IES LM-83 Plot			
Always Open			
Always Closed			

Table 1-4 Comparing Fully, Partially and Non-Daylight Area in All the Space Types




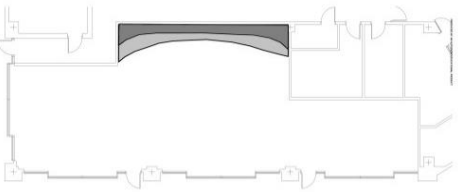
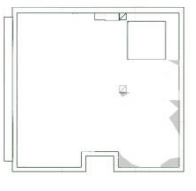
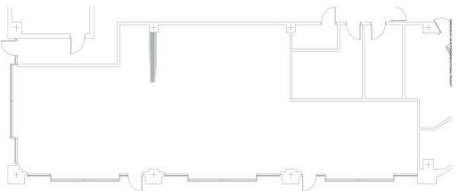
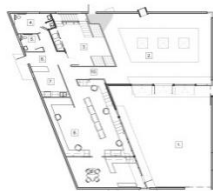
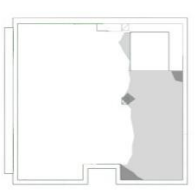
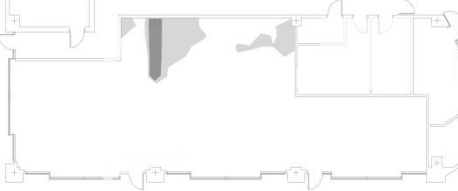
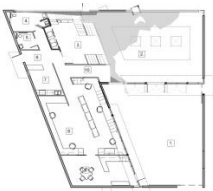
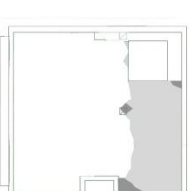
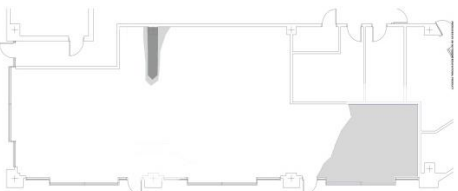
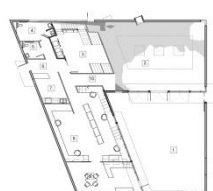
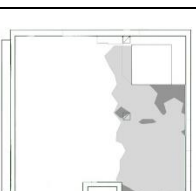
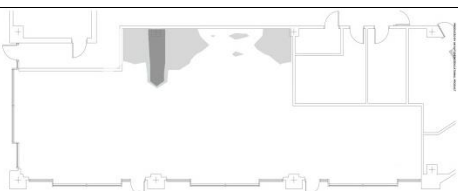
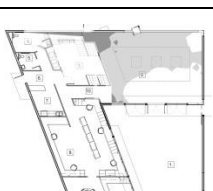
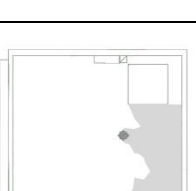
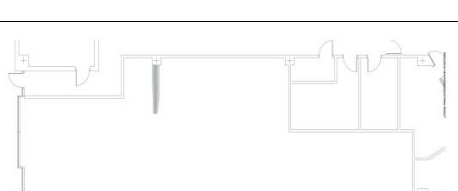
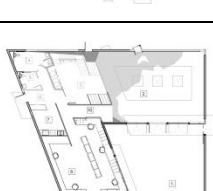
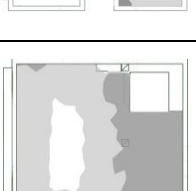
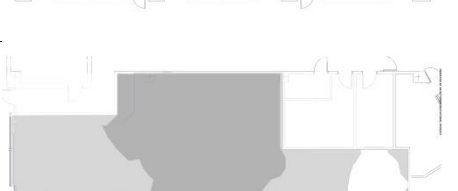
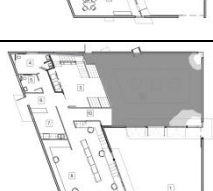


	# 014 ASE=10.6 	# 015 ASE=32.48 	# 016 ASE=18.89 
Type of Blind	Roller Fabric Shade	Roller Blind	Curtain Accent
Students' Evaluation	-----		-----
Point-in-time simulation			
Blindswitch-A Plot			
Blindswitch-B Plot			
IES LM-83 Plot			
Always Open			
Always Closed			

Table 1-4 Comparing Fully, Partially  and Non-Daylight Area  in All the Space Types




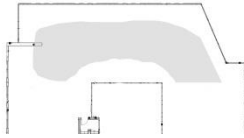

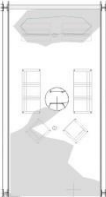
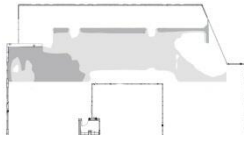
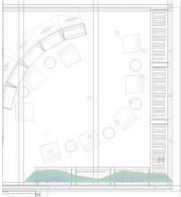
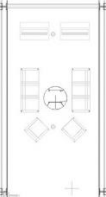
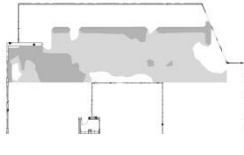


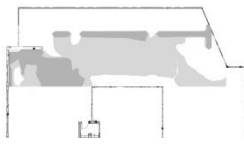
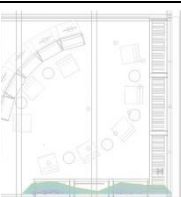

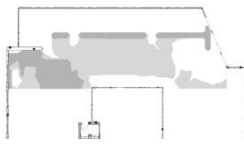
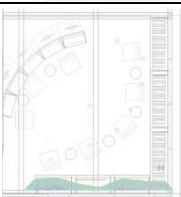

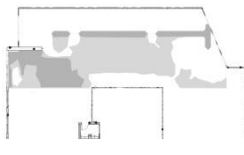
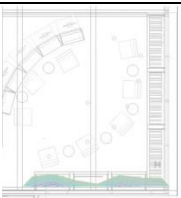
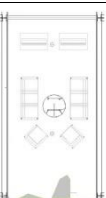
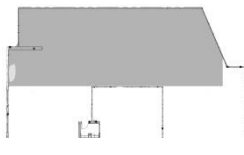
	# 018 ASE=36.89 	# 019 ASE=0 	# 020 ASE=6.28 
Type of Blind	Louver Blind	Louver Blind	Louver Blind
Students' Evaluation	-----	-----	
Point-in-time simulation			
Blindswitch-A Plot			
Blindswitch-B Plot			
IES LM-83 Plot			
Always Open			
Always Closed			

Table 1-4 Comparing Fully, Partially  and Non-Daylight Area  in All the Space Types




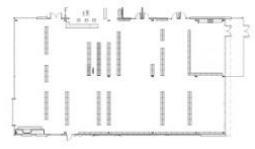
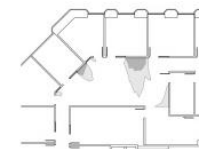

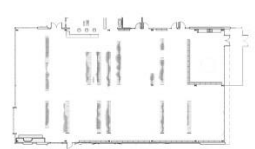
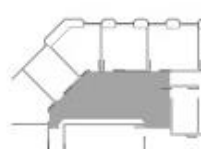

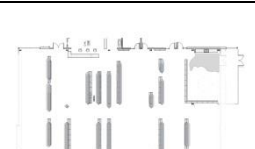
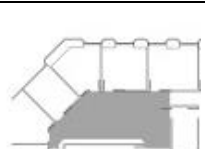
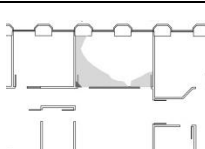

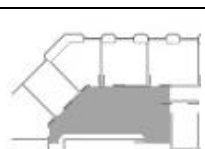
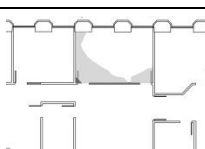

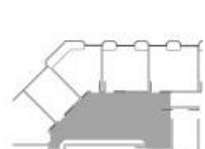
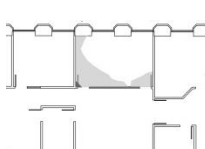

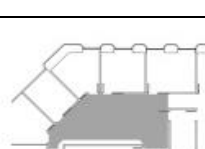
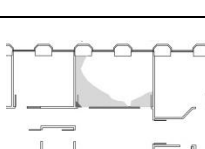
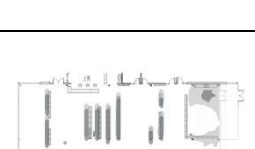
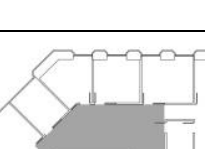
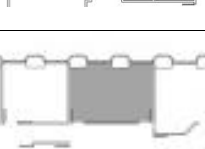
	# 021 ASE=12.96 	# 010 ASE=0 	# 011 ASE=0 
Type of Blind	Roller Blind	Louver Blind	Louver Blind
Students' Evaluation			
Point-in-time simulation			
Blindswitch-A Plot			
Blindswitch-B Plot			
IES LM-83 Plot			
Always Open			
Always Closed			

Table 1-4 Comparing Fully, Partially  and Non-Daylight Area  in All the Space Types



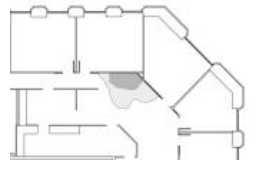
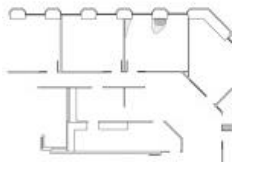
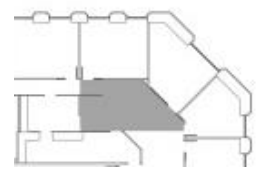
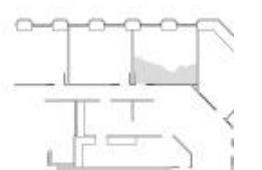
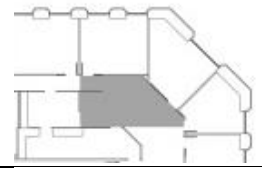
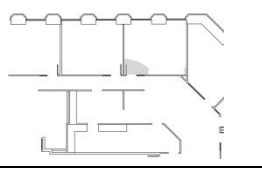
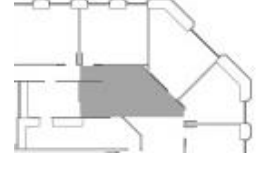
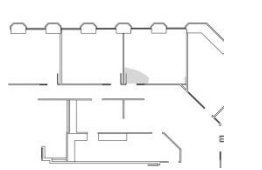
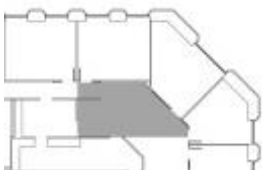
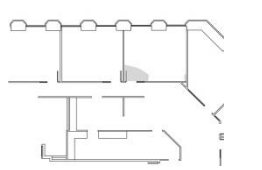
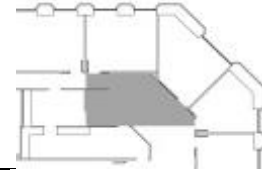
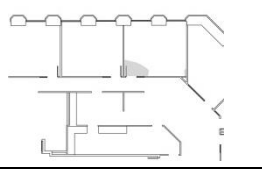
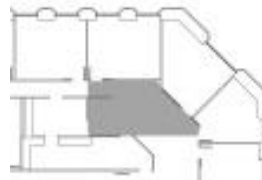
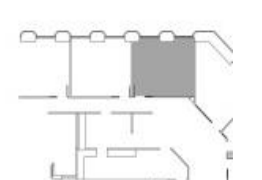



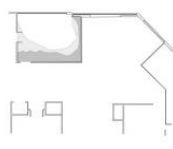
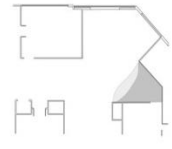

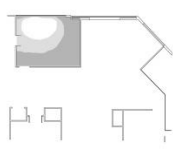
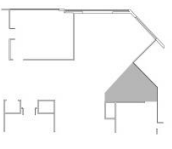

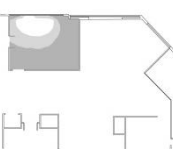
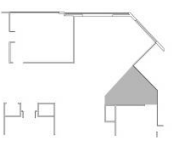
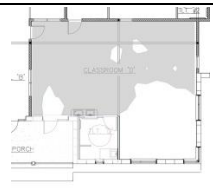
	# 012 ASE=0	# 013 ASE=0
		
Type of Blind	Louver Blind	Louver Blind
Students' Evaluation		
Point-in-time simulation		
Blindswitch-A Plot		
Blindswitch-B Plot		
IES LM-83 Plot		
Always Open		
Always Closed		

Table 1-4 Comparing Fully, Partially and Non-Daylight Area in All the Space Types

	# 002 ASE=0 	# 003 ASE=0 	# 004 ASE=1.18 
Type of Blind	No Blinds	No Blinds	No Blinds
Students' Evaluation			
Point-in-time simulation			
Always Open			






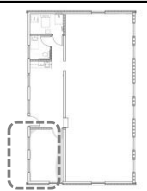
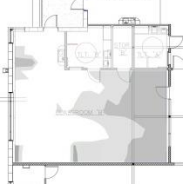


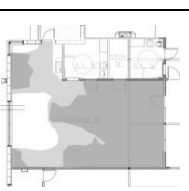




	# 005 ASE=12.02 	# 006 ASE=19.2 	# 007 ASE=15 
Type of Blind	No Blinds	No Blinds	No Blinds
Students' Evaluation			
Point-in-time simulation			
Always Open			

Table 1-4 Comparing Fully, Partially  and Non-Daylight Area  in All the Space Types



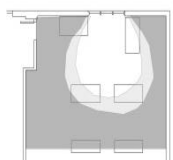

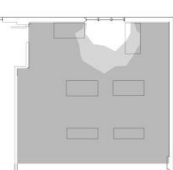
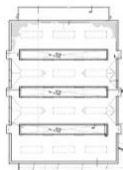
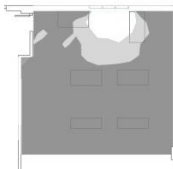
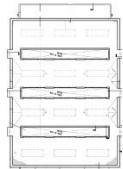
	# 017 ASE=3.76 	# 022 ASE=0 
Type of Blind	No Blinds	No Blinds
Students' Evaluation		
Point-in-time simulation		
Always Open		




Table 1-4 Comparing  Fully,  Partially and  Non-Daylight Area in All the Space Types

Table 1-5 Comparing sDA values for always open, always closed, LM-83, Blinds witch-A and -B and ASE in all study spaces with students' drawings "non-daylit", "partially daylit" and "fully daylit".

NB: Spaces with no blinds installed do not have any value of sDA for three manual blind control patterns.

Space Number	sDA Always Open	sDA Always Closed	sDA LM-83	sDA Blinds witch-A	sDA Blinds witch-B	ASE	Student's evaluation - % Area "non daylit"	Students' evaluation - % Area "partially daylit"	Students' evaluation - % Area "fully daylit"	Student's Prediction Status	LEED V4	
											sDA	ASE
# 001	50.63	0.25	<u>41.6</u>	41.81	41.05	10.33	32.29	11.10	<u>57.16</u>	<u>Incorrect</u> Under predict	Fail	Fail
# 008	98.97	93.85	<u>97.95</u>	96.39	98.45	2.59	1.83	11.67	<u>86.50</u>	<u>Correct</u>	Pass	Pass
# 009	85.50	51.48	<u>83.73</u>	82.74	85.12	2.08	3.47	8.00	<u>88.53</u>	<u>Correct</u>	Pass	Pass
# 014	73.33	10.88	64.91	68.2	69.61	10.6	No Evals.	No Evals.	No Evals.	---	Pass	Fail
# 015	98.19	13.32	<u>87.58</u>	91.16	85.03	32.48	1.71	5.88	<u>92.41</u>	<u>Correct</u>	Pass	Fail
# 016	67.05	3.88	57.53	65.15	51.47	18.89	No Evals.	No Evals.	No Evals.	---	Pass	Fail
# 018	93.55	93.55	93.55	93.55	93.55	36.89	No Evals.	No Evals.	No Evals.	---	Pass	Fail
# 019	93.24	90.54	93.24	93.24	93.24	0	No Evals.	No Evals.	No Evals.	---	Pass	Pass
# 020	81.28	1.02	<u>79.87</u>	67.31	75.38	6.28	0.00	39.07	<u>60.93</u>	<u>Incorrect</u>	Pass	Pass

# 021	93.16	85.02	<u>92.88</u>	91.22	92.42	12.96	0.00	0.00	<u>100.00</u>	<u>Correct</u>	Pass	Fail
# 010	0.37	0.37	<u>0.37</u>	0.08	0.08	0	0.63	3.93	<u>95.45</u>	<u>Incorrect</u> Under predict	Fail	Pass
# 011	62.5	0.74	<u>62.5</u>	62.5	62.5	0	3.62	17.05	<u>79.33</u>	<u>Near</u> <u>Correct</u> Under predict	Pass	Pass
# 012	0.64	0.64	<u>0.64</u>	0.04	0.04	0	9.75	24.36	<u>65.89</u>	<u>Incorrect</u>	Fail	Pass
# 013	86.32	0.85	<u>86.32</u>	86.32	86.32	0	1.21	3.99	<u>94.80</u>	<u>Correct</u>	Pass	Pass
# 002	<u>15.05</u>	0.49	NB	NB	NB	0	23.15	23.11	<u>53.82</u>	<u>Incorrect</u>	Fail	Pass
# 003	<u>1.20</u>	1.20	NB	NB	NB	0	58.85	41.15	<u>0.00</u>	<u>Correct</u>	Fail	Pass
# 004	<u>33.20</u>	0.78	NB	NB	NB	1.18	2.21	5.67	<u>92.18</u>	<u>Incorrect</u> Under predict	Fail	Pass
# 005	<u>18.08</u>	0.38	NB	NB	NB	12.02	4.94	47.69	<u>47.37</u>	<u>Incorrect</u>	Fail	Fail
# 006	<u>97.62</u>	87.3	NB	NB	NB	5.2	0.00	10.08	<u>90.10</u>	<u>Correct</u>	Pass	Pass
# 007	<u>97.22</u>	2.38	NB	NB	NB	15.0	0.00	16.35	<u>83.91</u>	<u>Correct</u>	Pass	Fail
# 017	<u>6.51</u>	0.47	NB	NB	NB	3.76	58.26	15.80	<u>25.94</u>	<u>Incorrect</u>	Fail	Pass
# 022	<u>98.22</u>	54.38	NB	NB	NB	0	0.00	14.73	<u>85.55</u>	<u>Correct</u>	Pass	Pass

Table 1-5 indicates that 9 of 18 (50%) spaces are correctly predicted as either partially (nominal) or fully (preferred) daylit by the LM-83 blind control algorithm relative to students' evaluations. The other nine spaces were consistently under predicted by LM-83, suggesting that students found them to be either partially or fully daylit but the simulation predicted the spaces to be non-daylit 50% of the time.

According to the table 1-4 and 1-5, the Blindswitch-A, -B, LM-83 and always open results for spaces #011 and #013 are exactly the same. Windows in those spaces faced to the North and according to Nezamdoost et al. 2014 average percent occlusion for LM-83 in north façade is zero; for Blindswitch-B, the North facade never reaches the minimum vertical exterior illuminance trigger (33,000 Lux) and Blindswitch-A shows only 0.49% occlusion. So it is expected to have similar values in those spaces facing to the north.

In spaces #018 and #019 the existing blinds located on small windows and big windows have no blinds. So, blind occlusion does not have any considerable impact on amount of daylight in the study space; and that's the reason that sDA for always open, always closed (except for space #019), LM-83, Blindswitch-A and -B are all the same.

In plots of space #015, Blindswitch-A and -B, a large non-daylit zone can be seen on the east side of space which is due to the logic behind Blindswitch-A and -B algorithms. According to the algorithm, windows were assigned a number from 1-10 in random fashion, and each number had one of four blind operation types assigned. Window #1-2 are engaged and window #9-10 are always retracted. (Van Den Wymelenberg (2012) , Dyke et. al (2015) and Nezamdoost et al. (2014)).

Table 1-5 also shows sDA values for always open, always closed, LM-83, Blindswitch-A and -B and ASE in all study spaces. In this table, study spaces were also evaluated based on LEED V4. According to LEED V4, acceptable spaces are those with at least 55% spatial Daylight Autonomy_{300/50%} (sDA_{300/50%}) and no more 10% annual sunlight exposure_{1000,250} (ASE_{1000,250}). It is worth noting that LM-83 does not propose formal criteria for ASE_{1000,250} as it does for sDA_{300/50%}. The criteria of a 10% limit on ASE_{1000,250} was a LEED V4 committee determination.

Figure 1-9 shows the three alternate manual blind control algorithms (Blindswitch-A, -B, and LM-83) plotted next to the always open and always closed blind conditions for study spaces with blinds installed. While the plot cannot yet say which of the algorithms are most representative of actual human control patterns in these buildings, some interesting trends are noticeable which may guide future development of these algorithms.

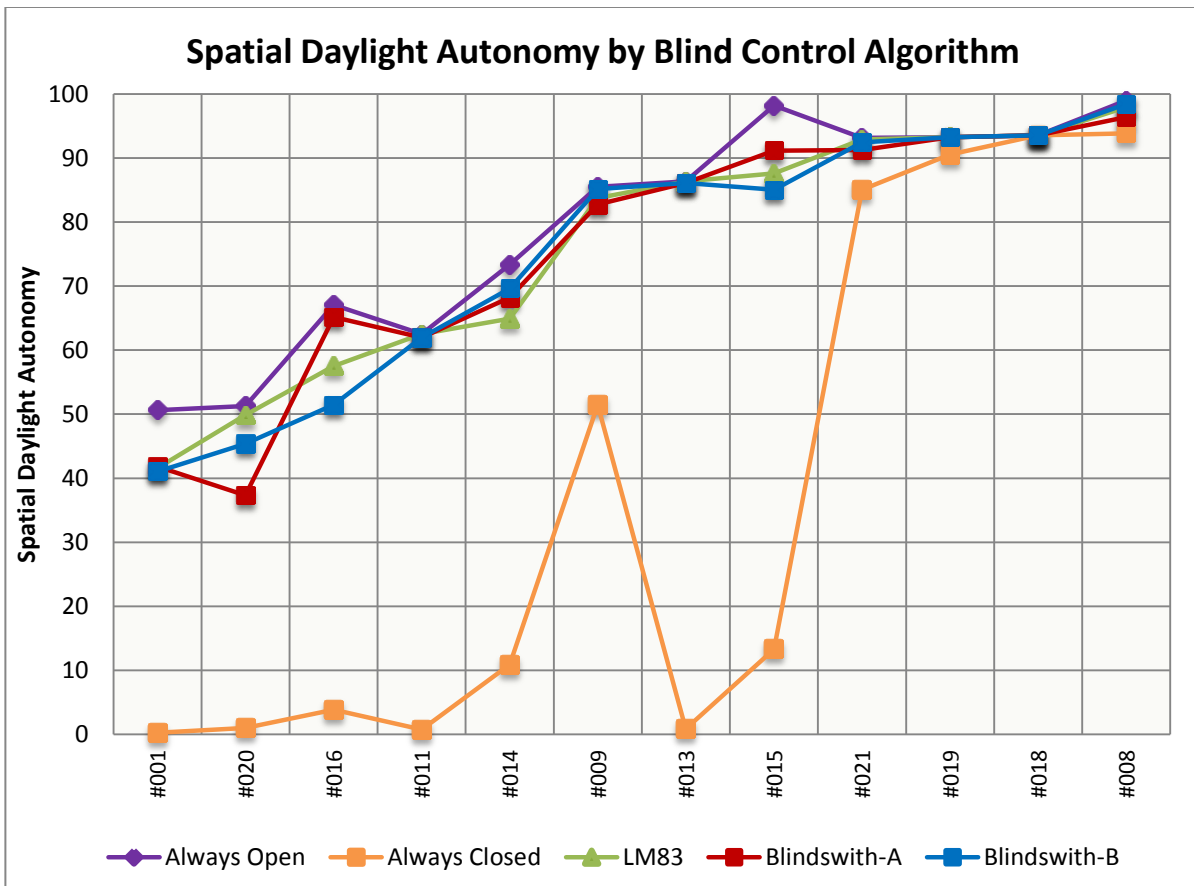


Figure 1-9 sDA plot by blind control algorithm sorted by LM-83 values

Moreover, in order to examine performance of three leading manual blind control patterns in detail, annual average of daily number of blind movements (NBM), annual average of daily rate of change (ROC) and annual average percent of blind occlusion were calculated and analyzed in 10 study spaces with blinds installed (Figure 1-10, 1-11 and 1-12 respectively). Previous research has only examined these variables for the alternate blind control algorithms in one or two spaces, so these findings are important with regard to understanding the usefulness of these algorithms for future research.

ROC is calculated to determine how many blinds move per day, that is, whether a particular blind either engages or retracts at least one time per day. However, ROC does not

take into account how often a particular blind changes per day. Therefore, NBM is required, as it shows the ratio of the total number of blind movements per day to the total number of blinds that moved (at least once) per day per façade (Dyke et al. 2015).

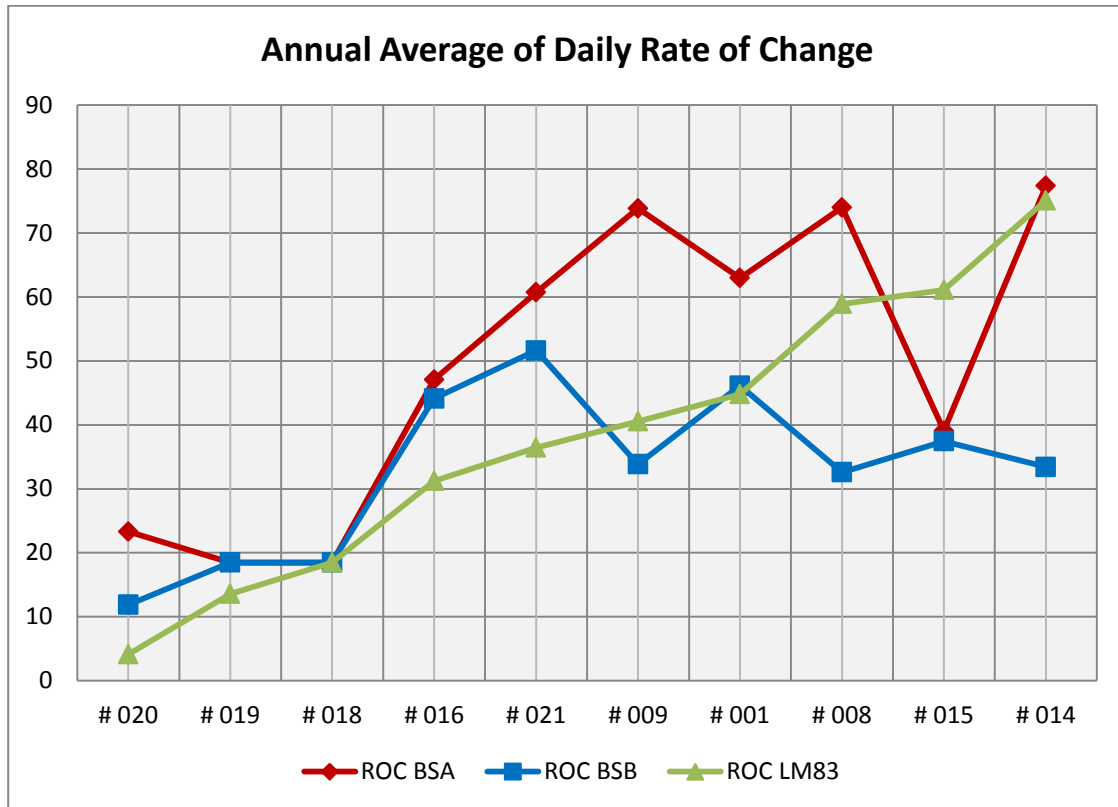


Figure 1-10 Roc plot for 10 study spaces

ROC plot sorted by LM-83 values (figure 1-10) reveals a few findings that are worth noting:

- Total ROC values are calculated based on the average ROC in all the window groups in all facades that have impact on study spaces. The quantity of window groups, as well as the number of orientations, matter, and may show considerably different results versus those spaces with only one window or one orientation. For example, in space # 020 there are 11 window groups on the north façade, and since the north

façade has little blind activity, this brings down the average ROC which also includes more active west facing blinds.

- Overall, Blindswitch-A shows highest rate of change (the most active algorithm) between three manual blind control algorithms.
- The lowest ROC values were recorded in spaces in Seattle (WA) versus Boise (ID), which is not surprising, given that Seattle has more cloudy days – 226 days for Seattle versus 155 days for Boise.

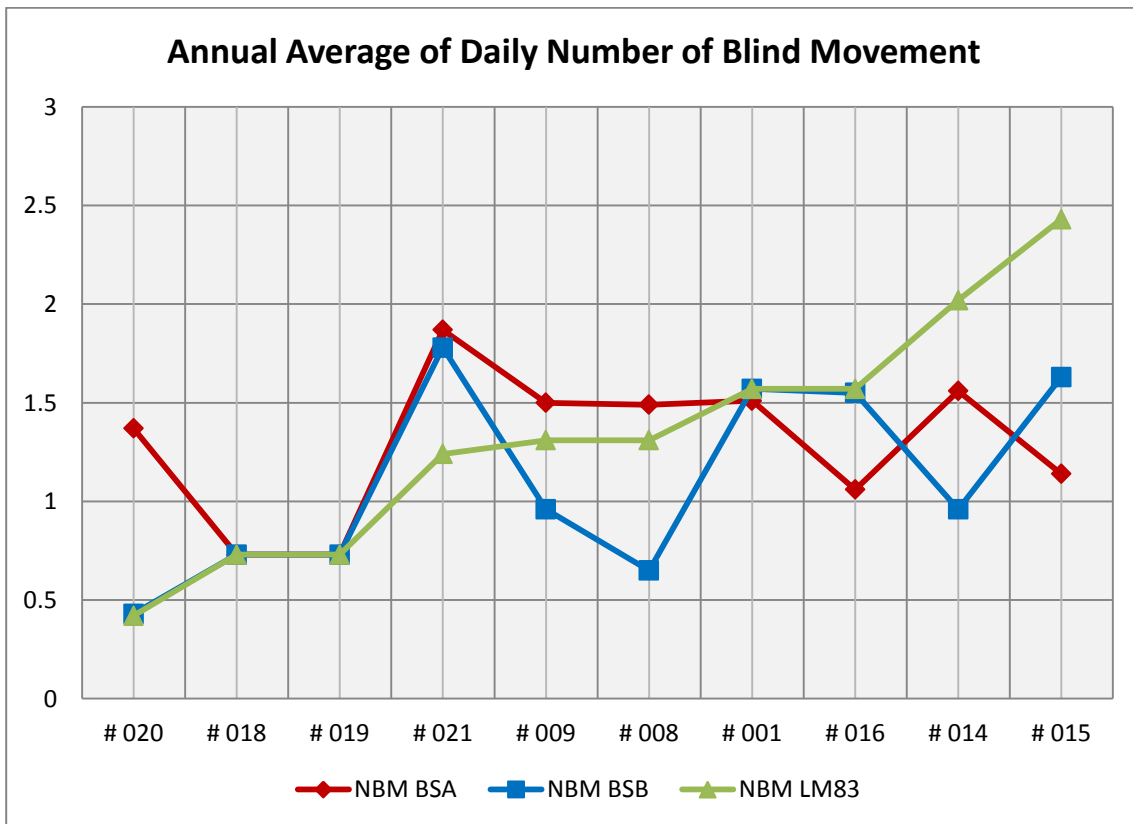


Figure 1-11 NBM plot for 10 study spaces sorted by LM83

Figure 1-11 compares annual average of daily Number of Bind movement (NBM) values of 10 study spaces sorted by LM-83, and below are the major points:

- In general, the highest NBM were reported for Blindswitch-A, except those spaces with overhangs. As expected, installing overhangs caused considerable decrease in NBM values for Blindswitch-A due to its logic – sun penetration depth set point (spaces #014 - #015 and #016).
- Blindswitch-B shows the lowest NBM in those spaces facing north (spaces #008 and #009).
- NBM of Blindswitch-A, -B and LM83 were reported with similar values in spaces #018 and #019, likely because most windows do not have blinds.
- Although the sample size is small, the highest NBM was reported in those spaces facing south -spaces #001, #015 and #021 (for all algorithms).

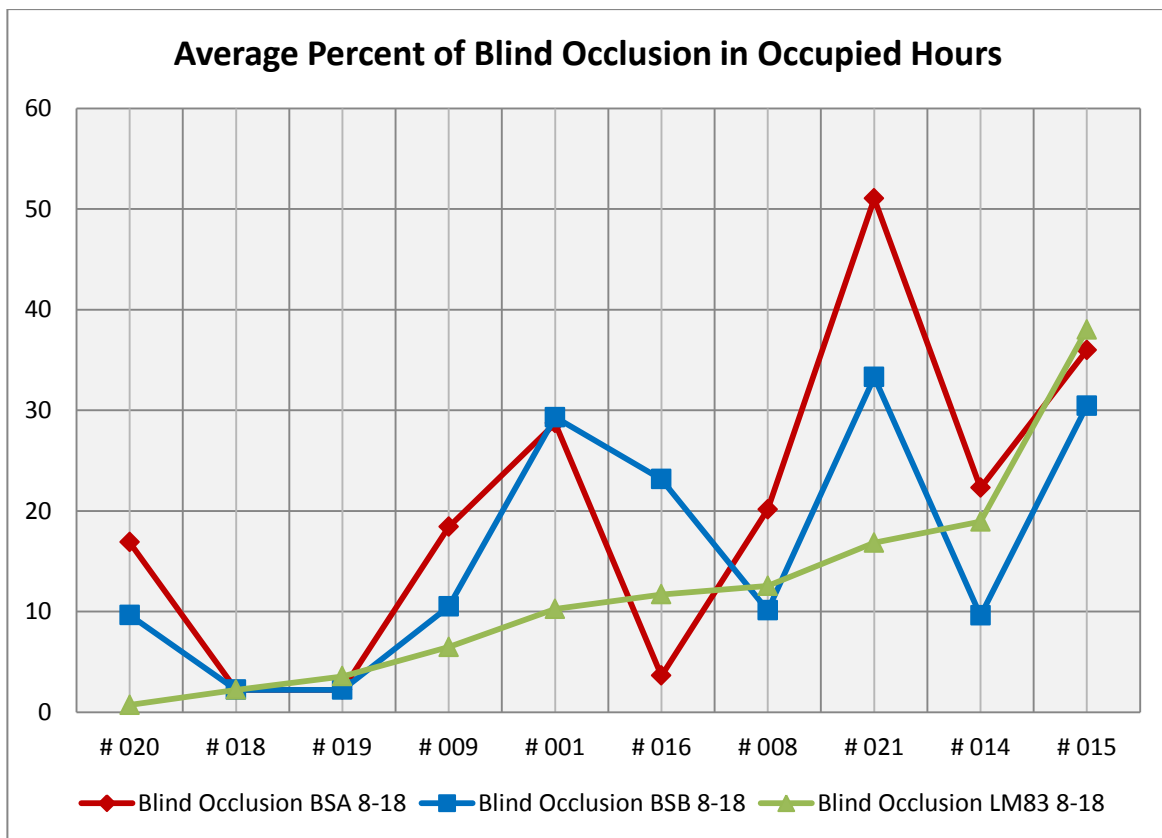


Figure 1-12 Average percent of blind occlusion for 10 study spaces (sorted by LM-83)

Figure 1-12 compares annual average percent of blind occlusion in 10 study spaces sorted by LM-83. The major findings are:

- Generally, windows are covered more based on Blindswitch-A than other algorithms. However, there is an exception— space #016, which is due to the exterior obstruction. The gallery space is obstructed with office space on west side (16' height) and 8.5'-height-wall on east side.
- LM-83 is generally the least occluded algorithm in 10 space study sample.
- The highest occlusion was recorded in spaces facing south for all three algorithms (spaces #001, #015 and #021).
- In a few spaces (spaces #001, #015 and #021), considerable discrepancies can be seen in the occlusion values of Blindswitch-A and -B versus LM83. It is due to unfortunate limitation of Blindswitch-A and -B in smaller spaces with only one or just a few windows. (Nezamdoost and Van Den Wymelenberg, 2015). Blindswitch-A and -B were developed for larger spaces with more windows, ideally, a minimum of 10 windows.
- The low occlusion values for spaces #018, #019 and #020 in Seattle, show the sensitivity of blind algorithms to climate (62 % cloudy day in Seattle versus 43 % in Boise).

3.2 Point-in-time vs. Annual simulation

As noted above, and detailed in Table 1-4, the general shapes and sizes of the non-, partially and fully daylight areas of students' daylight evaluations and the simulated point-in-time daylight illuminances show notable similarities. In contrast, greater discrepancy can be

seen between the annual illuminance plots relative to students' evaluations. In order to test this visually identified trend, Figure 1-13 was plotted, comparing the percent of difference of fully daylit areas for point-in-time simulation and annual simulation (using 300 Lux based on IES LM-83 documentation) versus students' evaluations.

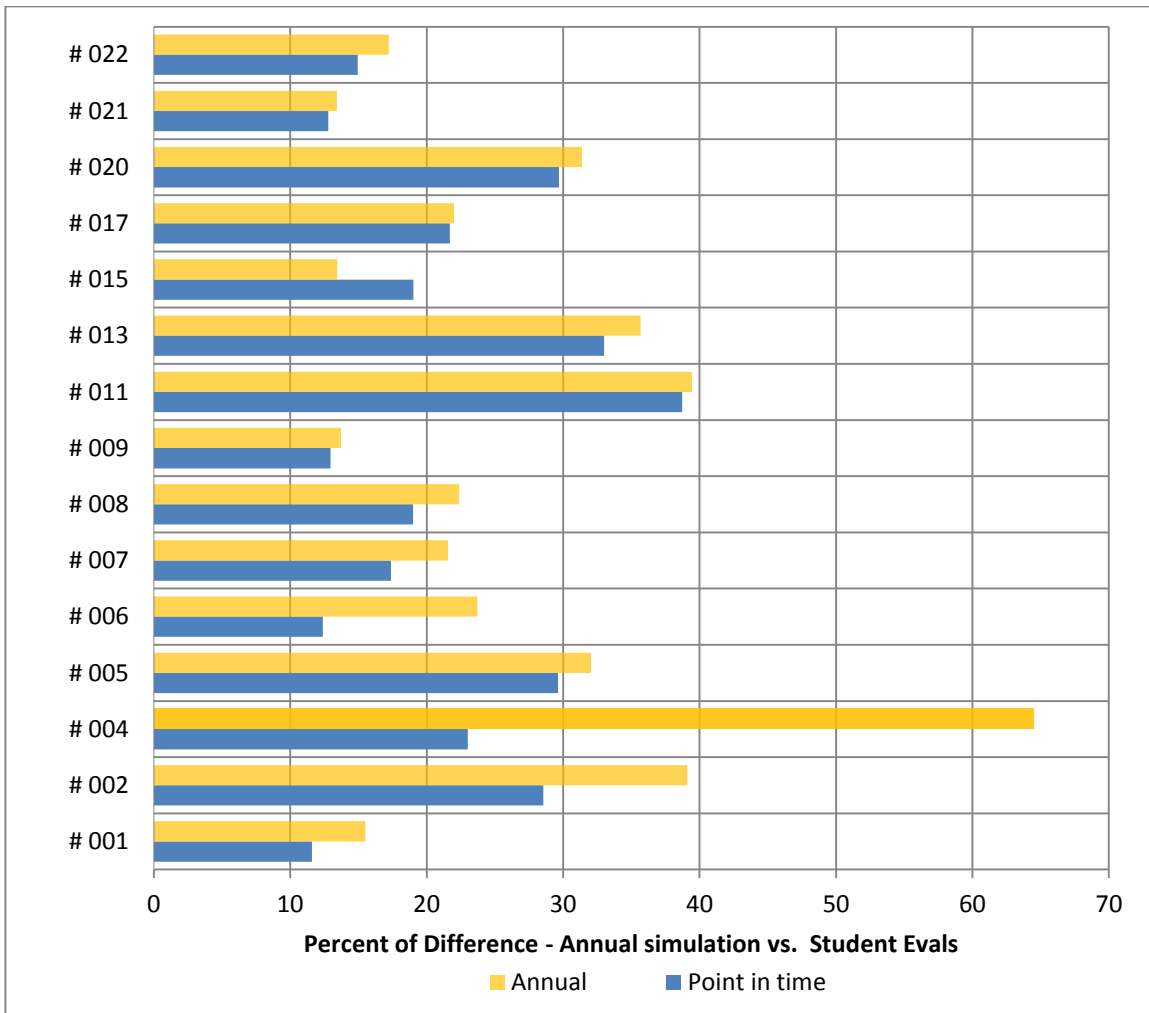


Figure 1-13 Comparing percent of difference in point-in-time and annual simulations

3.2.1 Point-in-time illuminance threshold

Given the increased accuracy of point-in-time simulations with regard to student evaluations outlined in Section 3-1, a wide varied range of illuminance thresholds were chosen and examined in order to find out the most accurate threshold based on students'

evaluations for the delineation of fully, partially and non-daylit areas. The sensitivity analysis went through illuminance levels from 50 Lux to 450 Lux (50, 75, 100, 125, 150, 175, 200, 250, 300, 350, 400, 450) for fully, partially and non daylit conditions in all study spaces separately and then compared with students' perception (daylit boundary drawings) and analyzed percent of total difference, percent of correct prediction, false negative and false positive errors. The purpose was to identify which threshold resulted in the highest correct prediction for fully, partially and non-daylit areas and thus produced the lowest discrepancy.

Figures 1-14 shows example of this procedure in non-daylit category in space #001. In each plot, the black color shows the similarity between students' evaluations and point-in-time simulation with specific thresholds. The green color illustrates false negative error, meaning that simulations disagree that the area is fully/partially/non-daylit (the result is negative) but it is in fact present in students' daylit evaluations. This scenario is reversed for the yellow zone, meaning that simulations determined a fully/partially/non-daylit area in point-in-time simulations (the result is positive), but it is not in fact present in students' drawings (the result is false).

Table 1-6 illustrates the detailed distribution of discrepancy for different illuminance levels for all the study spaces for the fully daylit category. Zero values were recorded in a few well daylit spaces which states that neither simulation results nor students' drawings reported any non-daylit zones.

Figure 1-15 graphically displays the sensitivity study to determine which illuminance indicator thresholds (ranging from 50-450 Lux) produced the smallest difference with students' assessments of fully daylit, partially daylit, and non-daylit areas within the study spaces. Additional analysis is revealed for sky condition and fenestration type.

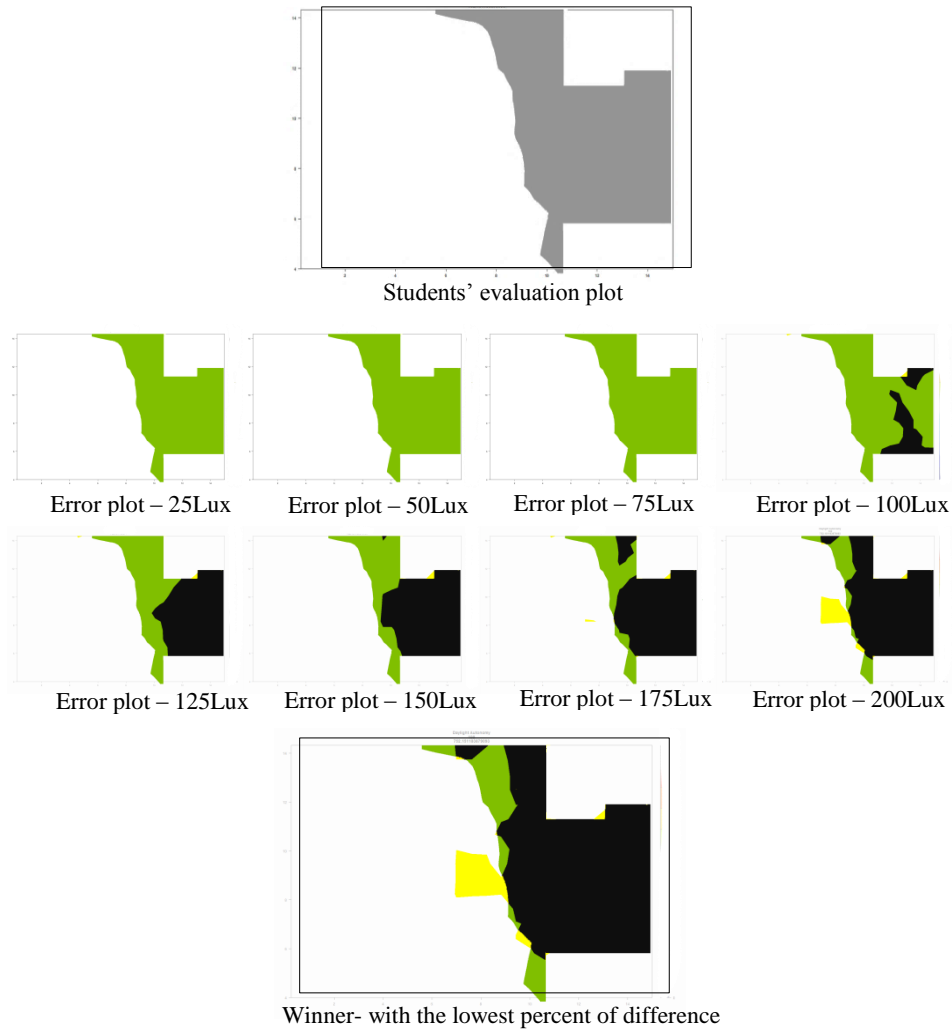


Figure 1-14 Non-daylit area discrepancy plots in range of 25Lux-200Lux illuminance level thresholds in one of study spaces- open office

Black: Correct – Green: False Negative Error – Yellow: False Positive Error

Table 1-6 Full daylit area - Distribution of discrepancy in different illuminance levels (100Lux-450Lux)

	100Lux(F)	150Lux(F)	200Lux(F)	250Lux(F)	300Lux(F)	350Lux(F)	400Lux(F)	450Lux(F)
# 001	42.72	25.70	17.89	12.17	11.58	12.34	16.84	22.78
# 002	27.48	23.54	24.03	25.43	28.55	32.54	37.59	41.62
# 003	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
# 004	6.89	7.51	8.33	10.76	23.00	39.41	46.35	51.52
# 005	58.95	51.35	42.02	34.88	29.62	26.56	24.79	26.02
# 006	16.72	17.39	17.39	17.39	17.39	17.39	17.39	17.39
# 007	10.03	11.83	11.90	12.11	12.39	12.71	13.06	13.20
# 008	14.40	20.94	20.94	20.94	19.01	15.77	13.27	13.80
# 009	5.72	4.55	5.12	7.54	12.96	24.39	34.70	45.96
# 011	6.18	7.74	13.66	23.22	38.74	47.42	54.05	59.01
# 013	6.59	6.59	9.97	14.54	33.01	44.91	52.71	58.40
# 015	18.71	18.62	18.55	19.12	19.03	18.94	18.87	18.76
# 017	12.81	15.70	18.31	20.37	21.70	22.63	23.33	23.93
# 020	46.19	47.87	43.84	30.22	29.69	31.21	33.43	35.36
# 021	9.86	10.47	11.37	12.13	12.79	13.60	14.37	15.24
# 022	15.09	15.09	15.09	15.09	14.95	14.91	19.94	34.99

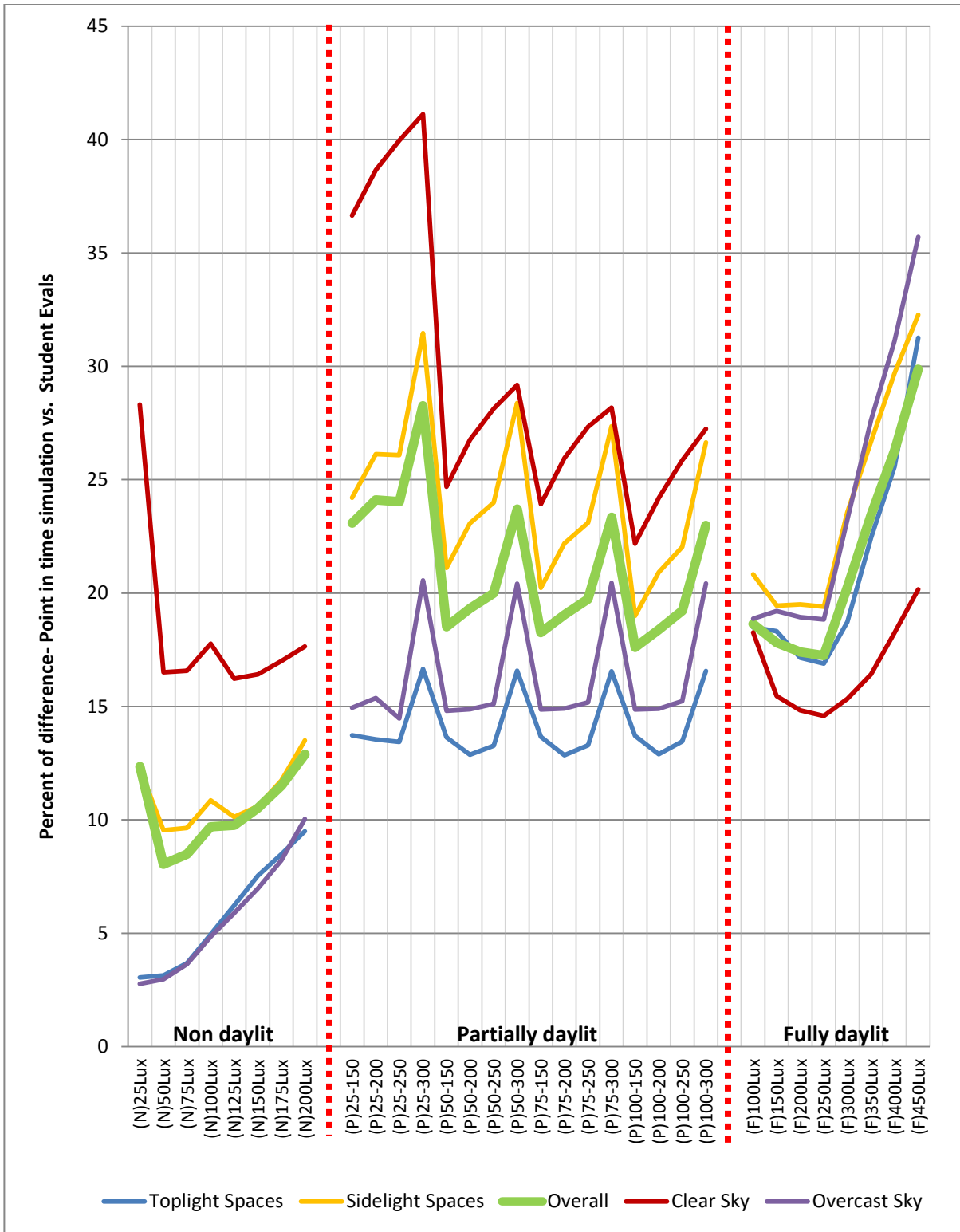


Figure 1-15 Sensitivity study on illuminance indicator thresholds (ranging from 50-450 Lux) for point-in-time data

3.2.2 Occupant Visual Perception

As it was mentioned in Section 3-1, in a few spaces (#004, #011 and #013) students' evaluations show a possible impact of human brightness perception increasing error in simulated illuminance plots relative to students' evaluations. This error generally happens when vertical glazing or clerestory openings provide high levels of daylight washing vertical surfaces and/or the ceiling of the study space. Consequently, this surface brightness can impact students' perception of daylit/non-daylit areas in a room while the horizontal task illuminance (simulation grid) does not necessarily exceed the required threshold to designate that area as daylit. To test this concept, two categories of study spaces were compared. The first group includes all study spaces and the second group consists of only spaces that do not meet the characteristics described above as contributing to the human brightness perception error (thus, excluding #004, #011 and #013). Figure 1-16 illustrates this comparison using the average difference of each group for specific illuminance thresholds. It is interesting to see that at higher illuminance levels (more than 200 Lux), the group two, without the spaces subject to occupant brightness perception issue described, produce lower discrepancy. The groups are statistically significantly different above 200 Lux ($p < 0.00075$).

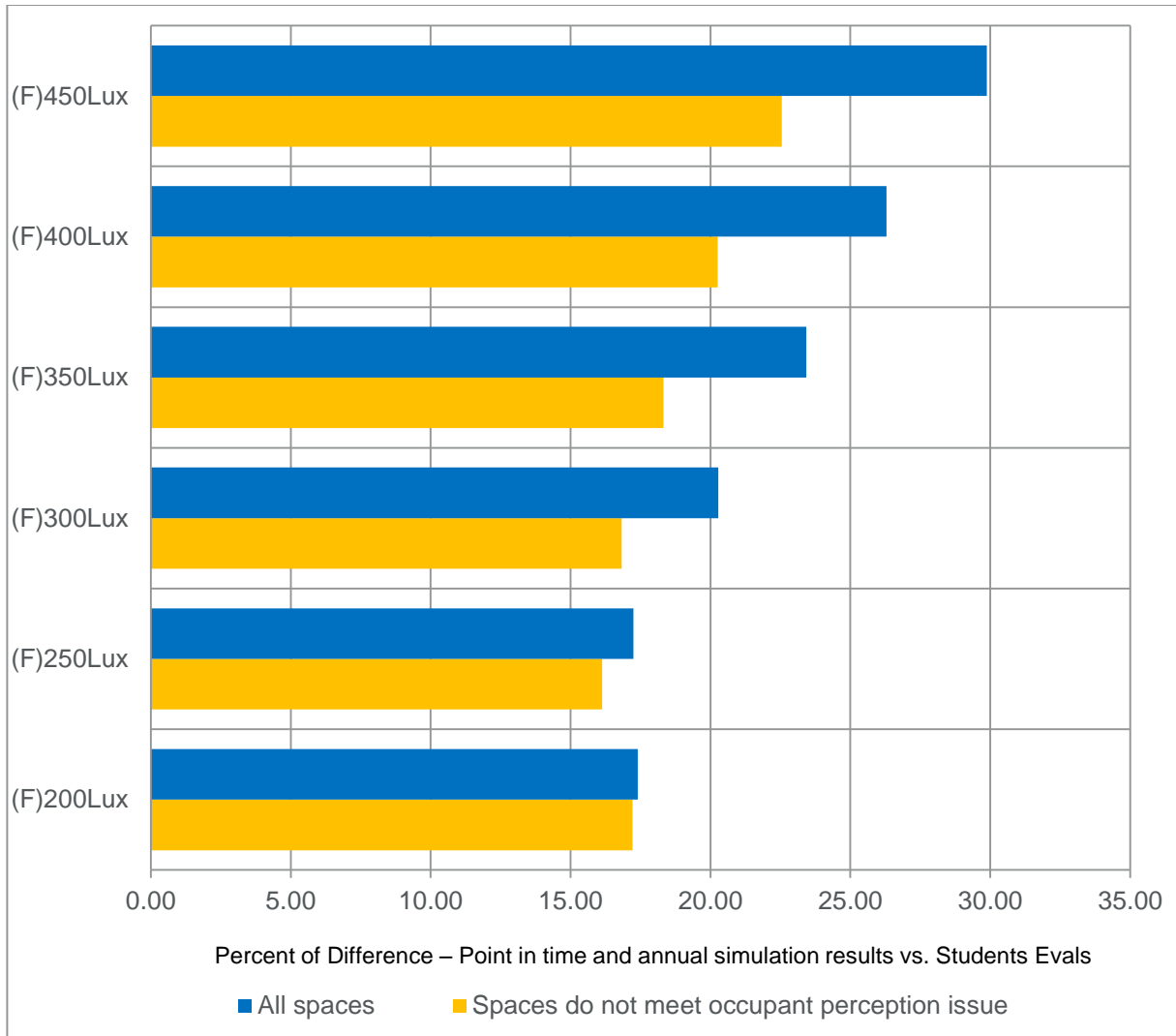


Figure 1-16 Comparing percent of difference with and without the spaces designated as having characteristics contributing to the occupant brightness perception issue – point-in-time simulation

4. Discussion

The research plan was conducted in order to determine which of three candidate manual interior blind control algorithms produced the smallest difference between annual daylight results and students' qualitative assessments of “non-daylight”, “partially daylit” and “fully daylit” areas of multiple field study spaces. At first glance, annual spatial daylight autonomy did not differ dramatically between manual blind control patterns. However sDA

values for Blindswitch-A are consistently lower than the other two algorithms (Blindswitch-B and LM-83). The average percent of difference of three manual interior blind control patterns, (Blindswitch-A, Blindswitch-B and LM-83) against students' evaluations are more or less in the same range: 9.47%, 9.17% and 8.97% in non-daylight category (illuminance value below 150 Lux, <150); 16.64%, 16.12% and 15.89% in partially daylit category (illuminance value between 150 and 300 Lux, $t > 150 \text{ lux}, < 300 \text{ lux}$); 21.25%, 21.86% and 20.16% in fully daylit category (illuminance value above 300 Lux, $> 300 \text{ lux}$);. However, LM-83 stands a little bit closer to what students evaluated in non-, partially and fully daylit areas. According to proposed indicator values (100 and 250Lux) the average percent of difference dropped: 6.84%, 6.67% and 6.69% in non-daylight category (illuminance value below 100 Lux, <100); 11.73%, 11.52% and 10.98% in partially daylit category (illuminance value between 100 and 250 Lux, $t > 100 \text{ lux}, < 250 \text{ lux}$); 15.09%, 16.09% and 15.53% in fully daylit category (illuminance value above 250 Lux, $> 250 \text{ lux}$). Among annual daylighting results, the lowest discrepancy belong to blinds open since in the experiments students were asked to pull blinds open. Accordingly it is reversed for results with blinds always closed.

Also, three alternate manual blind control algorithms (Blindswitch-A, Blindswitch-B and LM-83) plus always open and always closed blinds conditions were compared and analyzed according to spatial Daylight Autonomy (sDA) (in figure 1-9), annual average of daily rate of change (in figure 1-10), annual average of daily number of blind movement (in figure 1-11) and average percent of blind occlusion in occupied hours (in figure 1-12). At first glance it is interesting to see how close to the “always open” condition all three of the manual blind control algorithms are. A few other findings include:

- High values of sDA for the always closed blind position data in those spaces with skylight shows the importance of toplighting strategies to provide robust daylight performance even while all the windows are covered with closed blinds. At the same time, spaces with only vertical fenestration with blinds applied show very low values for the always closed condition, indicating how critical blind use is in annual daylight performance evaluation.
- The alternate manual blind control patterns (Blindswitch-A, -B and LM-83) are most forgiving, and least sensitive to spaces with north facing fenestration and toplighting. Spaces that used both toplighting and sidelighting strategies are robust against blind closure (spaces #008, #009, #018, #019 and #021). Spaces facing north (Spaces #011 and #013) show no considerable difference by blind algorithm while sidelit spaces with south, east and west orientation show greater difference by blind algorithm.
- Blindswitch-A, in most cases, reveals the highest rate of change value and percent of blind occlusion which results in slightly lower spatial daylight autonomy.
- LM-83 and Blindswitch-B alternate which produces the highest sDA of the three manual blind control algorithms. Sometimes Blindswitch-B shows higher sDA than LM-83 and vice versa, however the sDA values are fairly close in most cases for these two algorithms.
- For spaces with overhangs or light shelves, Blindswitch-A shows higher sDA values than Blindswitch-B and LM-83. Thus, Blindswitch-A appears to be more sensitive to those technologies than LM-83 or Blindswitch-B.
- LM-83 is generally the least occluded algorithm in 10 space study sample.

- The highest occlusion was recorded in spaces facing south for all three algorithms (spaces #001, #015 and #021).
- All three manual blind control algorithms show sensitivity to the climate zone.

Furthermore, evaluations were conducted using equivalent point-in-time daylighting results, blinds always open and always closed, as well as blind control algorithms previously mentioned. The result section has revealed that 71% (45 out of 64) of total point in time and annual simulation plots in table 1-4 according previously published indicator values (150, 300 lux) (Blinds always closed are excluded) in measuring non-daylit area and 56% (36 out of 64) in fully daylit area prediction, agree with students' evaluations with less than 20 percent difference. Also, the interesting side is that in all study spaces (except space # 015) point-in-time simulation results had less difference between student daylit area evaluations than did annual simulation results. Considering all study spaces, the average percent of difference in point-in-time simulation is 21.63% while 27.01% discrepancy was recorded for annual simulation. The difference of the means is statistically significant. With proposed indicator values (100 and 250 Lux) in both point-in-time and annual simulation more correct prediction and less discrepancy was recorded regarding to students' drawings. It decreased by 18.39% and 21.47% discrepancy in point-in-time and annual simulation respectively. It is interesting to note that space # 015 shows lower discrepancy in annual simulation versus point-in-time simulation, and this is the students' studio space where they spend a great deal of time on an annual basis. The reduced error for point-in-time results begins to answer the question posed by Van Den Wymelenberg (2014); is there an important difference between visual comfort research results obtained from naïve versus expert participants or occupants versus visitors?

This study does not provide a conclusive result since research participants were all students of architecture, cannot be considered completely naïve, nor are they daylighting experts.

Sensitivity studies were conducted to see which illuminance indicator thresholds (ranging from 50-450 Lux) produced the smallest difference when comparing students' assessments of fully daylight, partially daylight, and non-daylit areas within the study spaces. The following preliminary horizontal illuminance thresholds emerged from the sensitivity analysis as representing the least difference between student evaluations and point-in-time simulations; the threshold between non-daylit and partially daylight - 100 Lux; the threshold between partially daylight and fully daylight - 250 Lux (9.07 and 17.25 percent discrepancy respectively). These are slightly lower than previously published indicator values (150, 300 lux). This is possibly due to the relatively young sample of human participants in this study. Other thresholds could be argued as having the least discrepancy for certain conditions (sky condition, daylight aperture type). However, based on this study, these values (100, 250 Lux) are recommended for future use in annual-climate-based daylighting analysis because they are logical and represent consistently low error across multiples space types, times of year, aperture types and sky conditions.

More accurate results can be reached if we classify study spaces according to the exact sky condition that students evaluate the space – overcast or clear. Results indicate and explain that students predict dark conditions (non and partially daylight) better in overcast sky (average difference in all threshold-study spaces is 12.78%) while average difference was reported more than twice (25.69%) in clear sky. But in order to predict fully daylight areas in spaces, students showed lower difference in clear sky (16.66%) than overcast sky (24.19%). In clear sky, the least discrepancy were recorded in 125 Lux for non-daylit areas and in 250

Lux for fully daylit areas; while in overcast sky 25 and 250Lux are the best boundaries in non/partial and partial/full daylit zones respectively.

Similarly, the overall data were classified and analyzed under two different daylighting strategies: Toplighting and sidelighting. In all three categories- non, partial and full, students could predict more accurately in those spaces using skylights plus windows - toplight spaces (5.82, 14.17 and 21.10% in average respectively) versus spaces with windows only – sidelight spaces (11.04, 24.12 and 23.92% respectively). In sidelight spaces according to comparative study of students' drawings and simulation results, 50Lux and 250Lux show lowest percent of discrepancies in non and fully daylit categories; while the winners in toplight spaces are 25 and 250Lux.

Finally, it was found that a moderating variable defined as “Occupant Visual Brightness Perception” had a statistically significant impact ($p < 0.00075$) on student evaluations of daylit areas in rooms with generally higher illuminance levels.

Finally, only eight of 22 spaces studied meet the LEED V4 criteria for the EQ daylight credit. However, of the 18 spaces with student daylit area drawings (from the 22), students designated that 11 spaces had more than 75% of the floor area as “fully daylit”. Furthermore, 14 of the 22 spaces meet the sDA (LM-83) portion of the LEED V4 EQ daylight credit, meaning that 6 of the 14 failed due to the ASE 10% threshold criteria included in LEED V4. It is the authors' opinion that this ASE threshold, as it is currently defined and calculated via simulation, may be too restrictive and warrants further research before it is implemented in additional reach standards or codes.

5. Conclusion

Results indicate that point-in-time simulation results with blinds retracted showed less discrepancy between student daylight area evaluations than did annual simulation results regardless of the blind operation algorithm used. Still, the better understanding of annual-climate-based daylighting metrics is essential. Therefore, substantial analysis is presented about both point-in-time and annual simulation results.

The paper also identifies and explains inconsistencies between alternate annual blind control algorithms with regard to determination of spaces as “nominally daylight” or having “preferred daylight” according to LM-83 terminology. For point-in-time analyses, student evaluations conducted under clear skies and in study spaces with only vertical fenestration showed greater discrepancy with simulated results for the “non-daylit” and “partially daylight” designations than those conducted under overcast skies and those in study spaces with toplighting. On the other hand, student evaluations conducted under overcast skies and in study spaces with only vertical fenestration showed greater discrepancy with simulated results for the “fully daylight” designation. Student evaluations and point-in-time simulation results were more similar in spaces with some toplighting component than those having only sidelighting regardless of sky condition.

There were statistically significant differences regarding the most representative horizontal illuminance indicator value for discerning between “non-”, “partially” and “fully” daylight areas. Interestingly, for “fully daylight” areas, the illuminance indicator value, 250 Lux, consistently emerged across sky conditions and daylight aperture types as having the least discrepancy with daylight area drawings. It was found that a moderating variable defined by the authors as “Occupant Brightness Perception” had a statistically significant ($p < 0.00075$)

impact on student evaluations of daylit areas in rooms with generally higher illuminance levels whereby students considered spaces to be better daylit in cases where walls opposite perimeter vertical fenestration were washed with daylight. The t-test suggests statistical significance, the sample of spaces with this condition is small and therefore, this should be considered a preliminary finding.

The following horizontal illuminance thresholds emerged from the sensitivity analysis as representing consistently low discrepancy between student evaluations and point-in-time simulation results; the threshold between “non-daylit” and “partially daylit” produced 100 Lux and the threshold between “partially daylit” and “fully daylit” produced 250 Lux. These are slightly lower than previously published indicator values (150, 300 lux). This is possibly due to the relatively young sample of human participants in this study. Other thresholds could be argued as having the least discrepancy for certain conditions (sky condition, daylight aperture type). However, based on this study, these values (100, 250 Lux) are recommended for future use in annual-climate-based daylighting analysis because they are logical and represent consistently low error across multiples space types, times of year, aperture types and sky conditions.

However, some big research gaps can still be seen. Based on this study, it is difficult to justify which manual blind control algorithm responds most similarly to the actual blind use patterns of real occupants. The candidate blind control algorithms are based large on one or two parameters and this behavioral phenomenon seems to be more complex and requires further research. It seems unlikely that the little difference shown between any of the manual blind control algorithms and the always open condition is representative of actual user behavior. Moreover, this study shows that current manual blind algorithms have

unrealistically high values in average hourly blind occlusion, number of blind movements and rate of change than what is generally expected from a manual blind in reality. Therefore, it seems still there is a long way to make comprehensive pattern which improves accuracy of predictive energy and daylighting modeling. Future work should continue to update the proposed manual blind control algorithms based on additional human factors and post occupancy studies of manual blind use in real buildings.

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CHAPTER 2

Sensitivity Study of Annual and Point-in-Time Daylight Performance Metrics: A Twenty-Four Space Multi-Year Field Study

With the latest published version LEED (v4), and the IES codifying two recommended annual-climate-based daylighting metrics and performance criteria, annual daylighting simulation has become even more important to the design professions than ever before. However, interpretation and application of annual-climate-based daylighting data are still relatively novel. This paper documents a 8-year human factors daylighting field research project using students' qualitative assessments of daylight sufficiency and corresponding point-in-time and annual-climate-based daylighting simulation in a variety of building types (n=24) in order to provide insight to the building performance simulation community about application of these new annual daylighting metrics.

Results indicate that point-in-time simulation outcomes show considerably higher correlation values between students' subjective responses of daylight sufficiency than do annual simulation results. Still, the better understanding of annual-climate-based daylighting metrics is essential. Therefore, sensitivity analysis of illuminance thresholds was conducted for both point-in-time and annual daylight simulation results. The sensitivity analysis on horizontal illuminance thresholds consistently represents high correlation with students' subjective responses and point-in-time simulation results at 250 Lux for daylight sufficiency. For annual analyses, a range of thresholds from 100 lux to 300 lux shows the best fit to students' qualitative assessments, although low illuminance thresholds are not statistically reliable due to not normally distributed data. At high levels of daylight illumination, very poor R^2 values in glare questions confirm the previous studies that there is not substantial evidence for an upper limit being defined (HMG PIER 2012; Heschong and Van Den Wymelenberg, 2012).

It was found that spaces with very bright vertical surfaces, a moderating variable defined as "Occupant Visual Brightness Perception", had a statistically significant relationship with students' subjective responses to vertical surface brightness questions. By excluding those spaces demonstrating characteristics consistent with this

moderating variable, average correlation values improved from $r^2=0.44$ to $r^2=0.60$ in point-in-time, and from $r^2=0.21$ to $r^2=0.43$ in annual simulation results, specifically at illuminance thresholds greater than 250Lux.

Preliminary analysis suggests that the ASE 10% threshold criteria may be too restrictive and may result in seemingly well-daylit and visually comfortable spaces not achieving the metric. Therefore, a case study analysis of 19 study spaces and was conducted and compared several alternate *nHours* (250, 300, 600 and 900 hours) criteria as proposed by HMG-PIER Review 2012, as well as the maximum number of hours that any one single point in entire room received of direct sunlight (simulated 1000 Lux). At 250 and 300 hours exceeding 1000 Lux direct sunlight, almost half of study spaces failed, having results higher than 10%. While a few study spaces face northwest and the sun only comes in to small part of the space in the late afternoon and is not really a problem. Two of study spaces are reading rooms where people can choose where to sit. This suggests that perhaps temporal or space type sensitivity should be applied to these criteria. However, it appears as though ASE 1000 Lux 250 hours at 10% threshold warrants refinement.

Two variations of daylight autonomy, spatial continuous $DA_{300\text{Lux}/50\% \text{ time}}$ and spatial $DA_{300\text{Lux}/50\% \text{ time}}$ were analyzed and compared. Generally, most of the study spaces produce very high values for spatial continuous $DA_{300\text{Lux}/50\% \text{ time}}$. In fact, 15 out of 19 spaces produce values higher than 90% of the floor area as “daylit” using this metric. This means that study spaces may produce very similar cDA values despite important performance differences making it a difficult metric to use for codes, reach standards, or design decision making. It is possible that a higher illuminance indicator value used with continuous DA could prove more useful at providing this important discernment ability.

1. Introduction

During the last decade, the architecture industry has experienced many metrics for measuring daylighting in built environment. Static daylight metrics measured at a single point in time such as Daylight Factor (Moon & Spencer 1942 and Waldram 1909) and LEED 2009

9AM/ LEED 2009 3PM, have recently fallen out of favor and instead annual dynamic daylighting metrics such as Daylight Autonomy (Reinhart et al. 2006), Useful Daylight Illuminance (Mardaljevic and Nabil, 2005), continuous Daylight Autonomy (Rogers, 2006), Daylight Saturation Percentage (Collaborative for High Performance Schools, 2006) were promoted in order to better incorporate project design parameters, climate, and the annual variability of daylight. In 2012, the Illuminating Engineering Society (IES) formalized this evolution when they adopted spatial daylight autonomy (sDA) and annual sunlight exposure (ASE), which were the first human-factors evidence-based daylight metrics approved by IES. And consequently in 2014, sDA and ASE were codified by the latest version of LEED as one of two modeling compliance paths for Indoor Environmental Quality (EQ) Daylight Credit, offering more potential credits than the other compliance pathways.

According to LEED V4, acceptable spaces are those with at least 55% of floor area exceeds 300Lux for 50% of annual occupied hours (spatial Daylight Autonomy_{300Lux/50% time} (sDA_{300/50%})) and no more than 10% of analysis points in a space exceeds 1000 Lux of direct sunlight for 250 hours as measured from 8AM-6PM (annual sunlight exposure_{1000 Lux, 250 hours} (ASE_{1000, 250})). Nezamdoost and Van Den Wymelenberg (2015) examined LEED V4 criteria for the EQ Daylight Credit on 22 spaces but only eight spaces passed. Fourteen of the 22 spaces met the sDA (LM-83) portion of the LEED V4 EQ Daylight Credit, but six of the 14 failed due to the ASE 10% threshold criteria. The ASE criteria adopted by LEED appears to be too restrictive and may result in many good daylighting designs failing to meet the credit.

Moreover, LEED V4 criteria work to emphasize the use of manual and automated glare control devices in buildings to protect occupants from sunlight exposure and subsequent glare and thermal stress. Designers are encouraged not to over-glaze buildings and to

implement manual or automated blinds in their projects to mitigate unnecessary direct sunlight. Blind use impacts have long been ignored in standard energy and daylight simulation practices but recent research has proposed candidate manual blind control algorithms and stressed the importance of their use in annual performance simulations (Dyke et al. 2015, Nezamdoost et al 2014, Nezamdoost and Van Den Wymelenberg 2015).

In recent years, a number of researchers have attempted to determine whether occupants use manual interior blinds according to predictable patterns or not: Lightswitch 2002 by C.Reinhart, Blindswitch-A 2012 and –B 2012 by Kevin Van Den Wymelenberg, and IESNA LM83 – Daylight Metrics Committee 2012. Although the availability of current candidate algorithms might encourage using interior blinds in daylight and energy simulations, the results do not clearly distinguish which is the most likely predictor of blind use in reality. A few studies were conducted to compare energy consumption of current manual blind control patterns (Van Den Wymelenberg 2012, Nezamdoost et al. 2014, Dyke et al. 2015) and daylit area evaluations by students (Nezamdoost and Van Den Wymelenberg. 2015); but unfortunately, there has been very little data available to determine which algorithm(s) best correlated with occupant satisfaction, preference, or predicted blind position. Furthermore, according to previous field studies there remains a lack of consensus regarding which variables are most likely to dictate manual blind use (Van Den Wymelenberg et al. 2012).

Given the need for data sets to test the viability of current annual daylight performance metrics, a substantial human factors field study was conducted. This field study included qualitative assessment of 24 real daylit spaces by graduate architecture students and annual and point in time simulation of daylight performance.

2. Methods

The research plan was conducted to address one primary goal and several secondary objectives. The primary purpose of this paper was to understand how well annual simulated daylight results for daylight sufficiency and excessiveness correlate with students' qualitative assessments within 24 study spaces. This paper follows up on a previous study conducted by Lisa Heschong (HMG-PIER Review 2012, Heschong and Van Den Wymelenberg, 2012). The secondary objectives were to test correlations of subjective responses with alternative point-in-time illuminance thresholds (ranging from 100-5000 Lux), percent time and illuminance thresholds for annual analysis, alternate manual blind algorithms in annual analysis, alternative thresholds for annual sunlight exposure, and whether continuous (spatial) daylight autonomy performs better or worse than standard spatial daylight autonomy. There was also interest to determine if any other illuminance metrics or modifiers improve correlation of annual simulation results with subjective responses.

2.1 Data Collection

2.1.1 Experiment Setup

This paper documents an eight year long experiment (2007-2015) conducted with architectural graduate students (n=81) at the University of Idaho in Boise who took course "Daylighting Design and Simulation" to evaluate 24 real study spaces by documenting their own intuition about daylight performance. During 43 field trips, the students were asked to independently¹ evaluate each space's daylight performance using questionnaires. A total of 448 unique evaluations were collected.

¹ "Please visit the study space during the field trips and individually conduct your assessment without consulting with other students."

Human factors evaluations were conducted during field trip observations in 24 spaces within 14 buildings in Boise, Idaho (43.62° N and 116.20° W) and Seattle, Washington (47.47° N and 122.32° W). The field trips occurred during class time, generally between the hours of 11 AM and 3:30 PM, with median time at 1:45pm. The research protocol (project 15-724) was reviewed by the Institutional Review Board at the University of Idaho and was certified as exempt. Figure 2-1 illustrates field trip observation dates, color-coded by sky condition (shown here as clear or overcast).

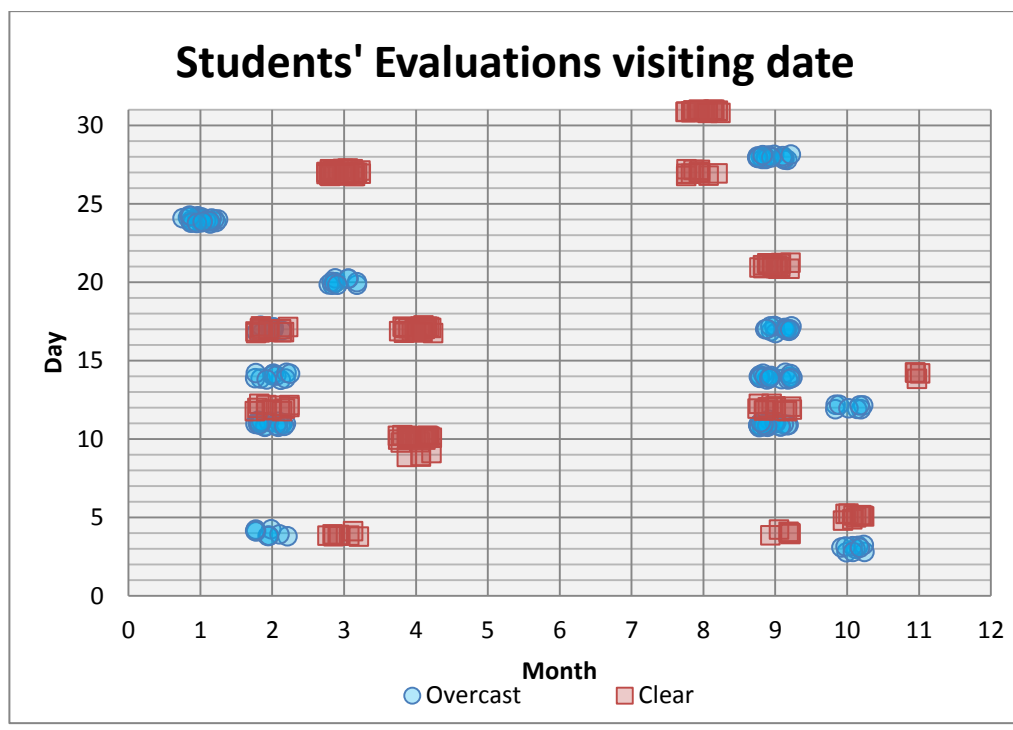


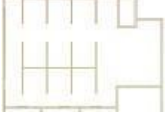



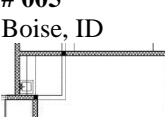
Figure 2-1 Students' evaluation dates, color coded by sky condition

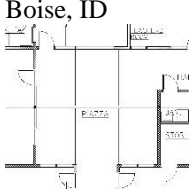

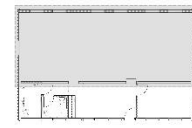

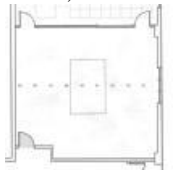

In order to be inclusive of a broad range of daylight conditions, study spaces were chosen with diverse building geometry, space type, orientation, size, daylight strategy (toplight/sidelight), sky condition, window glazing characteristics, and exterior obstructions. These are summarized below.

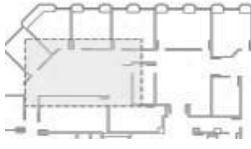

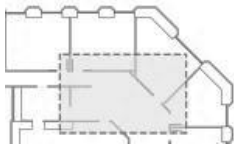
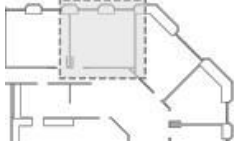


- I. Orientation: Out of 24 spaces, there are eight spaces facing north. Five and three spaces have west and south orientation respectively. Only one space is located on the east facade and two spaces are multiple-oriented. The remaining spaces are either toplight only or located in the core zones of buildings.
- II. Space Type: In order to ensure consistency with previous researches (HMG-PIER Review 2012, Heschong and Van Den Wymelenberg 2012) and address common space types that employ daylight and blinds, field study spaces were selected in three common space types.
- **1. Office space type (n=12)**: This category includes those spaces that generally have regular occupants during the year that work on computer, phone, and paper-based tasks at fixed desk locations and orientations. We placed emphasis on open offices (n=10) rather than private ones (n=2), since designing daylighting quality and blind operation is more complex in open rather than private offices.
 - **2. Classroom space type (n=6)**: This category was interpreted to those spaces with more flexibility in seating locations with different task orientations. Occupants mainly do desk work, usually discuss in groups, but typically face a single viewing direction (teaching wall). Conference rooms, meeting rooms and regular classrooms are good examples in this category.
 - **3. Other space type (n=6)**: The main characteristic of this space type is that it has potentially more visitors than regular users. They are allowed to move through entire space easily, choose where to stand, sit and work. This category generally includes wide range of open public spaces such as libraries, lobby areas, banking areas, galleries, gymnasiums, transportation lobbies and etc.

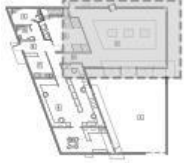



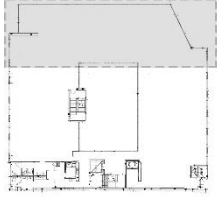

Table 2-1 shows each study space in details.

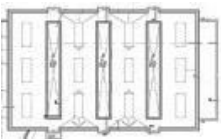
Table 2-1 Overview of Study Spaces

Building	Space Type	# students Evals.	Sky	Date of Eval.	Blind Type
# 001 Boise, ID 	Open Office	8	Overcast	10/12/2007	Horizontal 2-inch white Louver blinds
		11	Clear	2/12/2012	
# 002 Boise, ID 	Open Office	12	Clear	4/10/2012	No interior blinds- Overhang/North facing/Low VLT
# 003 Boise, ID 	Reception	12	Clear	4/10/2012	No interior blinds
# 004 Boise, ID 	Classroom	8	Overcast	9/28/2007	No interior blinds- Overhang
		11	Overcast	10/3/2008	
		12	Clear	3/27/2012	
		2	Clear	4/9/2015	
# 005 Boise, ID 	Conference Room	12	Overcast	3/27/2012	No interior blinds
# 006	Atrium	7	Overcast	9/28/2007	No interior blinds

Boise, ID 		21	Overcast	11/9/2010	
# 007 Boise, ID 	Office	12	Clear	3/27/2012	No interior blinds- Overhang
		2	Clear	4/9/2015	
# 008 Boise, ID 	Office	15	Clear	8/31/2007	No interior blinds- Overhang/Vegetation
		12	Overcast	3/20/2012	
# 009 Boise, ID 	Conference Room	9	Clear	8/31/2007	No interior blinds
# 010 Boise, ID 	Classroom	12	Overcast	1/24/2012	Horizontal White Louver blinds
		12	Overcast	4/17/2012	
		10	Overcast	2/11/2014	
		6	Clear	2/17/2015	
# 011 Boise, ID 	Open Office	10	Overcast	2/11/2014	Horizontal White Louver blinds
		6	Clear	2/17/2015	

# 012 Boise, ID 	Open Office	12	Overcast	4/3/2012	No interior blinds
# 013 Boise, ID 	Conference Room	12	Overcast	4/3/2012	Horizontal Louver blinds
# 014 Boise, ID 	Open Office	12	Overcast	4/3/2012	No interior blinds
# 015 Boise, ID 	Private Office	12	Overcast	4/3/2012	Horizontal Louver blinds
# 016 Boise, ID 	Open office	11	Clear	8/27/2008	Roller Fabric shade - Overhang
		19	Clear	8/31/2010	
# 017 Boise, ID 	Studio	10	Overcast	2/4/2014	Roller blinds – Translucent overhang
		5	Clear	11/14/2008	
		3	Overcast	2/3/2015	
# 018 Boise, ID	Gallery	10	Clear	10/5/2007	Curtain Accent – Overhang +Light shelf
		12	Clear	9/12/2008	
		16	Clear	9/21/2010	

					
# 019 Boise, ID 	Open Office	12	Overcast	1/24/2012	No interior blinds
		12	Clear	4/17/2012	
# 020 Seattle, WA 	Periodical Reading Room (PRR)	9	Overcast	9/17/2007	Louver Blinds
# 021 Seattle, WA 	Stacks Reading Room (SRR)	9	Overcast	9/17/2007	Louver Blinds
# 022 Seattle, WA 	North Open Office	6	Overcast	2/17/2012	Atrium on south façade: Exterior motorized blinds—North, East and West: Louver blind
# 023 Ustick, ID 	Library-main space	19	Overcast	9/14/2010	South façade: Roller Shades
		12	Overcast	2/14/2012	
		10	Clear	3/4/2014	

# 024 Seattle, WA 	Gymnasium	7	Overcast	2/17/2012	No interior blinds - (Toplight)
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III. Room Size: The smallest space was a meeting room on the north side of an architects' office in Boise (#003) while the biggest study space is the main book stack room of a library in Boise with 7123 square feet area (#023). The median of room size in this field study is 997 square feet.

IV. Daylighting Strategy: The field study consists of 54% low sidelight spaces, 8% toplight spaces and 4% spaces with only clerestory windows. The remaining 34% spaces divided equally into low view windows and clerestory sidelight spaces (17%) and sidelight/toplight spaces (17%). Figure 2-2 shows the proportion of each daylighting strategy.

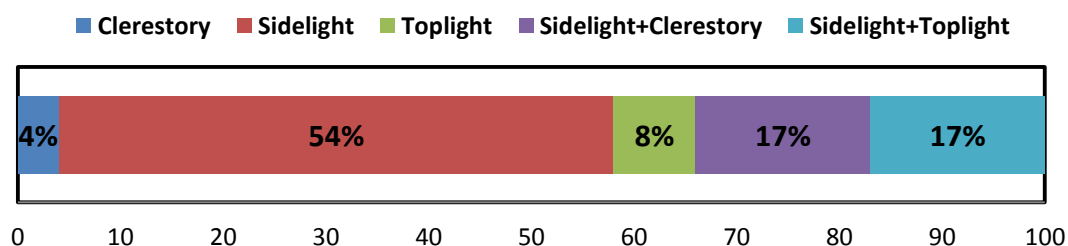


Figure 2-2 Comparing proportions of daylighting strategies in this field study

V. Shading Devices: Half of the sample is fitted with manual shades or blinds are composed (12 out of 24 spaces). Of the 24 spaces, 33% use horizontal slatted blinds, 13% have roller shades, and one space (4%) have a curtain accent (4%), as shown in figure 2-3. The study spaces without blinds use other solar control methods such as

overhangs (12%), translucent glass (13%), northerly orientation (17%), or vegetation (8%).

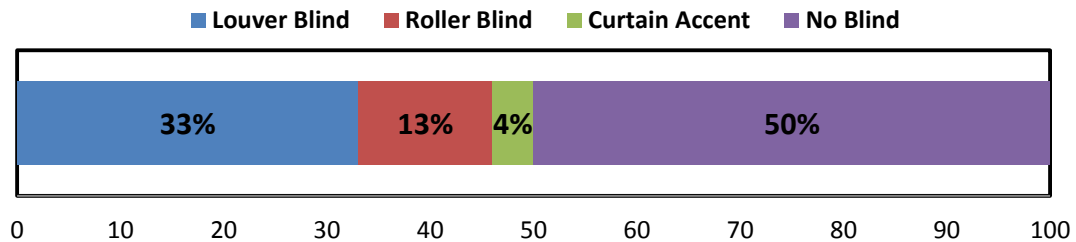


Figure 2-3 Comparing proportions of shading device types in this field study

- VI. Exterior Obstruction: Out of 24 study spaces there are three with built exterior obstructions that have a profound impact on daylight availability or block direct sunlight and five spaces use nearby trees for solar shading.
- VII. Window Glazing Characteristics: The visible light transmission (VLT) ranged from 36% to 75% with median 55% in this field study.
- VIII. Sky Condition: As the sun moves, it can meet sky conditions that could either strengthen or hidden it. It is essential to understand what the sky condition was in the time students evaluated the study spaces. Graduate students were asked to report sky condition during their evaluations. The most repetitive sky condition recorded for each field trip was used in the simulations to establish the sky data. Overall, overcast days were the most prevalent in this field study (55.8%), while 44.2% of field trips recorded clear sky condition.

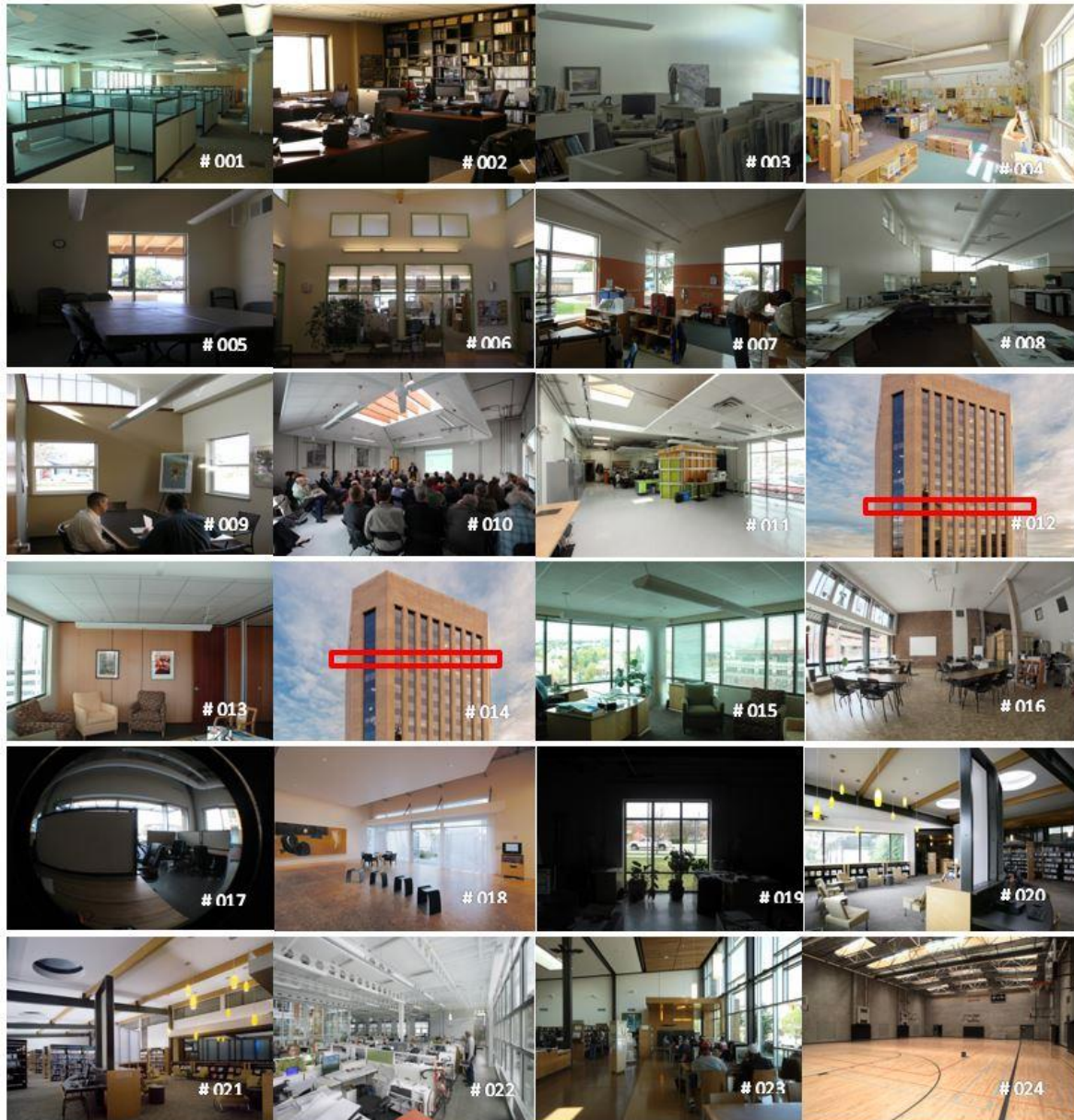


Figure 2-4 Photos of study spaces

Table 2-2 Experimental variables

Control (recorded) Variables	Time of day, time of year, sky condition, room design and all lighting conditions, blind position and electric lighting level (0-100 % dimmed)
Independent variables	Several candidate daylight performance metrics (daylight sufficiency, visual quality and blind operation), and thresholds of each.
Dependent	Human: subjective qualitative evaluations (questionnaires in Likert scales, etc.),

Variables

Environmental: building geometry, space type, orientation, size, daylight strategy (toplight/side-light), sky condition, window glazing characteristics, exterior obstructions and etc.

2.1.2 Participants

A total of 80 architecture graduate students (23 female, 57 male) under 30 years of age participated in this eight-year field study experiment. Figure 2-5 shows that students were asked to sit and walk around in study spaces for a period of time and then evaluate what would be representative of the average occupant experience of the spaces.

Table 2-3 shows occupants responses by space type more in details.



Figure 2-5 Evaluating one of study spaces by students during a field trip visit

Table 2-3 Occupants responses by space type

	Total	Avg. per space	Min	Max	# of space visit
Office	192	16	2	30	12
Classroom	124	21	2	40	6
Other	132	22	7	41	6
Total	448	19	--	--	24

2.1.3 Questionnaire items

Each participant completed a three-page questionnaire, focusing on visual interest (Question 1-5), daylight sufficiency (Question 11-15), lighting conditions (Question 6-10), visual comfort and glare (Question 16-20), and thermal/ acoustic privacy (Question 21-25).

The questionnaires started with 25 Likert-scale questions about the whole space specifically for the present conditions during the assessments (point in time). Additionally, 25 similar questions were asked, but this time asking the students to estimate performance considering an entire year and all sky conditions (annual, entire year). And finally, students were asked to evaluate study spaces based on sufficient daylight illumination, and problems regarding glare and sun penetration under specific sky conditions and seasons.

It is worth to note that a few study spaces were visited two or three times during the eight-year period of this study. So it was an opportunity to evaluate study spaces under different sky conditions (Refer to Table 2-1).

Among all 64 questions, the authors decided to focus more on a few specific qualitative questions which best represent the goals of this study. Each was given a letter and descriptor, as follows for analysis purposes:

A1- I enjoy being in this room – point in time.

A2- I enjoy being in this room – annual.

B1- I can work happily in this room with all the electric lights turned off – point in time.

B2- I can work happily in this room with all the electric lights turned off – annual.

C1- The daylight in this room is sufficient - point in time.

C2- The daylight in this room is always sufficient - annual.

BC1- Combination of questions B1 and C1- point in time.

BC2- Combination of questions B2 and C2- annual.

D1- The daylight in this room is not too bright - point in time.

D2- The daylight in this room is never too bright - annual.

E1- I like the daylight uniformity- point in time.

E2- I like the daylight uniformity- annual.

F1- I like the vertical surface brightness- point in time.

F2- I like the vertical surface brightness- annual.

G1- I am able to do my work here without any problems from daylight induced glare - point in time.

G2- I am able to do my work here without any problems from daylight induced glare - annual.

H1- I am happy with how the blinds are positioned – point in time.

- H2- I am happy with how the blinds/curtains can be operated – annual.
- I 1- There is no glare from direct sun penetration – point in time.
- I 2- There is low probability of glare from direct sun penetration – annual.

2.2 Simulation Parameters

Accurate three-dimensional digital models of each study space and surrounding exterior obstructions (within 100' of study space) were generated in SketchUp (version 2014). All relevant architectural details were included in digital models based on the simulation protocol outlined in LM-83 (IESNA-Daylight Metrics Committee 2012). Each geometry model was double checked with floor plans, site photographs and Google Earth. Once approved, the geometry was exported into RADIANCE daylight simulation engine using a two-foot by two-foot (2'*2') illuminance analysis grid (looking toward ceiling and located 32" above the floor) to generate horizontal illuminance point data sets.

Two bidirectional scattering distribution function (BSDF) files were created in LBNL WINDOW-7, for each operated window group (open and closed blinds) to use within the RADIANCE simulation engine. The blind type and visible light transmission (VLT) were considered and the BSDF supports the calculation of the patterns of light distribution through the window and blind operation.

In order to provide a relevant basis of comparison between the point-in-time simulations and the conditions present when the students conducted the evaluations during the field trips, a simulation data set with the same clock time, from the same week and with a matching sky condition from the annual simulation results was selected from within the annual hourly simulation results.

For annual dynamic climate-based daylight simulation, the three-phase RADIANCE method was employed (McNeil and Lee, 2013), per LM-83 (IESNA-Daylight Metrics

Committee 2012) with TMY3 weather file (analysis time period from 8AM to 6PM local clock time). Light source contributions were computed in RADIANCE by *Rcontrib* ambient calculations. Table 2-4 demonstrates RADIANCE simulation parameters used for all study spaces. Figure 2-6 illustrates examples of simulation output assigning both open (left plot) and closed (right plot) BSDF files in RADIANCE daylight simulation engine. Then, blind schedules are used to select the appropriate hourly data as relevant based on the blind condition being tested.

Table 2-4 RADIANCE Simulation Parameters

Ambient bounces	Ambient division	Ambient sampling	Ambient accuracy	Ambient resolution	Direct threshold
6	4096	1024	0.1	256	0

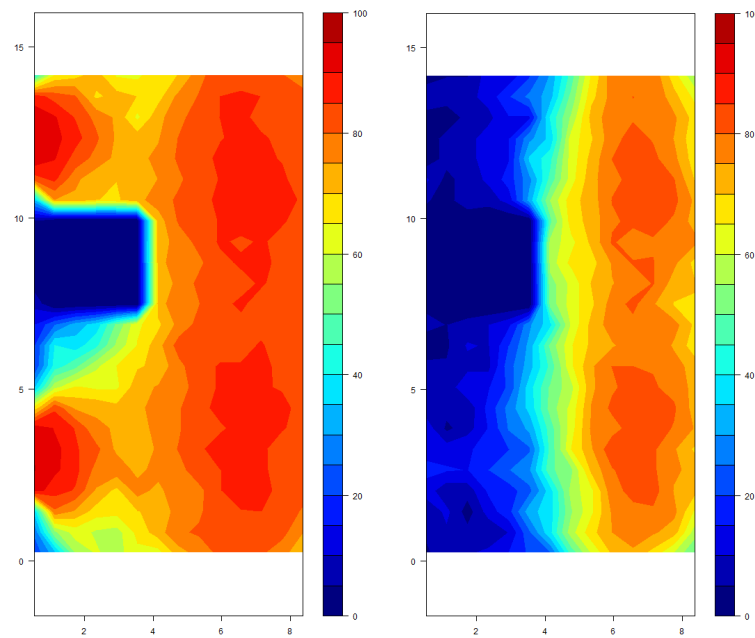


Figure 2-6 Example of simulation results with open (left) and closed (right) BSDF files – Space #011

Two substantial progressions of this paper from the previous daylight performance studies are that point-in-time analysis matching the sky condition during the field trip were

conducted and that alternate manual blind control algorithms were included in the annual simulations: Blindswitch-2012A, Blindswitch-2012B (Van Den Wymelenberg 2012) and IES LM-83 (IESNA-Daylight Metrics Committee 2012). Due to entirely different logic/documentation of manual dynamic blind algorithms, a few refinements and modifications were needed to apply: According to IES LM-83 2012 documentation, it is permitted to divide windows into as many “window groups” for blind control as desired by the simulationist. However, the Blindswitch-A and –B algorithms were proposed with precisely ten window groups on each facade. To reconcile this for spaces with only one or just a few windows, and no logical way to subdivide the window or windows into ten “window groups” for blind control, an approximate scaling with some randomization of the ten possible window group definitions from each (Blindswitch-A and –B) algorithm were applied . (Nezamdoost and Van Den Wymelenberg, 2015)

Based on IES LM-83 (2012) documentation (section 2.2.6 Blinds/Shades Operation): “...All exterior windows must be modeled with blinds unless: Blinds will not be installed according to design documents, and the Annual Sunlight Exposure calculation for the analysis area associated with the window group meets or exceeds the recommended criteria for “nominally acceptable” occupant.” As this research studies already built structures, only those exterior windows with blinds installed in reality were modeled as having blinds operated in the annual simulations.

To complete the workflow of daylight modeling for spaces with blinds, EnergyPlus was employed to calculate sun penetration depth and solar irradiance (see Dyke et al. 2015, Nezamdoost et al. 2014 for detailed workflow).

Figure 2-7 illustrates floor plan plots of three manually controlled blind patterns in space #017 with ten window groups facing south and three window groups facing west. From top to bottom: Blindswitch-A, Blindswitch-B and LM83.

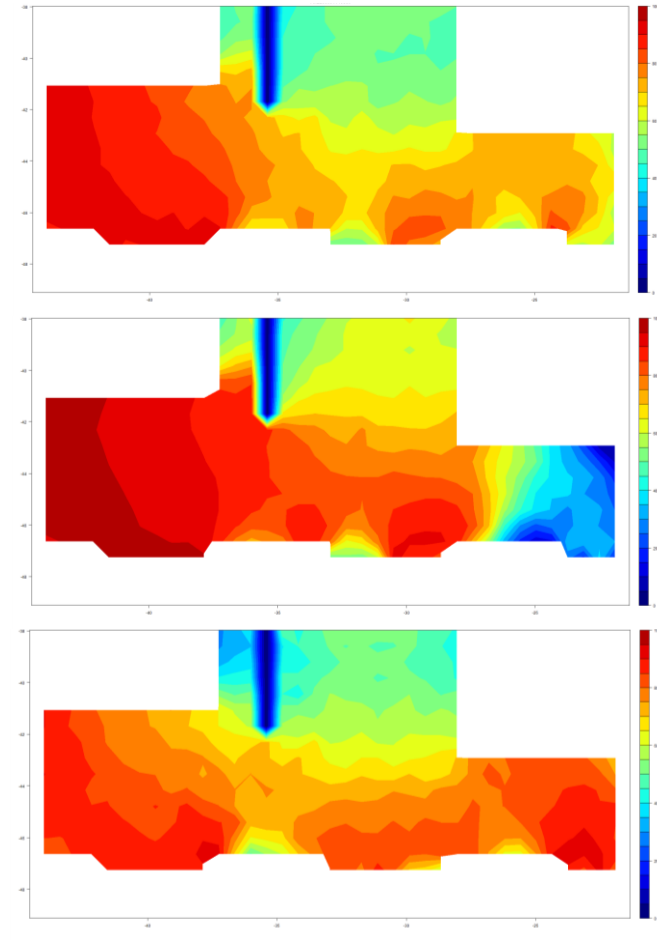


Figure 2-7 Examples of simulation results (DA plots) of three manual blind control algorithms in study space #017 from top to bottom: Blindswitch-A, Blindswitch-B and LM-83

2.3 Data Analysis

In this step, 448 questionnaires – 64 items each, were organized in spreadsheets. Scripts were used to conduct data cleaning; sanity checks were scripted for the entire data set, and redundant data entry was conducted for 10 percent of data to ensure accuracy. The approved data were imported as a single matrix to use in statistical analysis software (R). Inferential statistics were employed as follows: (1) one-way and two-way, paired and

unpaired t-test (95% confidence interval) to determine statistical significance between groups of continuous data. (2) Pearson Correlations were calculated to find the relationship between variables of interest. For the comparisons between simulations output and students qualitative assessments, simulation data set was categorized into two major metric types: (1) daylight sufficiency and (2) daylight excessiveness.

2.3.1 Daylight Sufficiency

Daylight sufficiency was conceptualized as a metric that could best predict occupant satisfaction with the amount of daylight illumination received in a space over the course of a year (HMG-PIER Review 2012). An illuminance indicator value and a percent of time value are fixed, for LM-83 it is 300 lux for 50% of the time between 8AM and 6PM, and the metric reports a percent area that meets these criteria. It is written $sDA_{300, 50\%}$. Given the increased implementation of the new metric, for example in LEED v4, and the resultant scrutiny placed upon it in the design research and professional communities, a follow up sensitivity analysis was warranted. This study examined simulation results using several illuminance levels (100-5000 Lux) and correlated results with students' qualitative assessments.

2.3.2 Daylight Excessiveness

According to Galasiu and Veitch (2006), both “too much daylight” as well as “too little daylight” may affect occupants' physical well-being. The IES DMC voted that a metric for daylight sufficiency should be paired with and balanced by a metric of daylight excessiveness so as to help reduce potential of occupant's perceived glare. So, the DMC developed a metric called *Annual Sunlight Exposure (ASE)* to serve as a visual comfort proxy by measuring annual potential for sunlight penetration. It is described as the percent of sensors that exceeds 1000Lux of direct sunlight illuminance, as measured by a

computationally simulated “zero-bounce” solar disc analysis, for more than 250 hours per year with blinds open. Given feedback from the research and design professional community regarding the 1000Lux threshold, other high illuminance thresholds (700, 800, 1000, 2000, 3000 and 5000 Lux) were examined as candidates for the “daylight excessiveness” threshold in both point in time and annual simulations.

3. Results

This section reports the findings of correlation coefficient analysis between annual simulated daylight results for daylight sufficiency and excessiveness, and students’ qualitative assessments within 24 study spaces. And then, test correlations of subjective responses with alternative point-in-time illuminance thresholds (ranging from 100-5000 Lux), percent time and illuminance thresholds for annual analysis, alternate manual blind algorithms in annual analysis, alternative thresholds for annual sunlight exposure, and whether continuous (spatial) daylight autonomy performs better or worse than standard spatial daylight autonomy. There was also interest to determine if any other illuminance metrics or modifiers improve correlation of annual simulation results with subjective responses.

3.1 Occupant Visual Brightness Perception Phenomena

A few spaces were identified to have the potential to be influenced by a moderating variable defined as “*occupant Visual Brightness Perception*” phenomena, potentially increasing differences in simulated illuminance plots relative to students’ subjective responses. According to Nezamdoost and Van Den Wymelenberg (2015), Students’ evaluations show a possible impact of human brightness perception increasing error which generally happens when vertical glazing or clerestory openings provide high levels of daylight washing vertical surfaces

and/or the ceiling of the study space. Consequently, this surface brightness can impact students' perception of daylit/non-daylit areas in a room while the horizontal task illuminance (simulation grid) does not necessarily exceed the required threshold to designate that area as daylit.

In order to test this idea, correlational analyses were run between related question items and the results show that the question, "I like vertical surface brightness" (labeled F) is highly correlated ($R^2= 0.625$) to question "The daylight in this room is always sufficient". The question, "I like vertical surface brightness" also shows strong correlation ($R^2= 0.7$) with question "I like the daylight uniformity". These findings support the hypothesis of "*Occupant Visual Brightness Perception*". This additional support suggests that annual daylight metrics should consider brightness of vertical surfaces. Table 2-5 reveals significant correlation of question F with other major questions in this study.

Table 2-5 Correlation results of vertical surface brightness versus Questions A, B, C, and E

Point in Time	A1	B1	C1	E1
F1	0.620	0.673	0.688	0.738
Annual	A2	B2	C2	E2
F2	0.594	0.591	0.626	0.707

Accordingly, the correlation coefficients values were plotted for both point-in-time (table 2-6) and annual (table 2-8) evaluations in two groups: The first category (Group 1) consists of all of the 24 study spaces and the second category (Group 2) includes only those spaces do not have characteristics likely to bias responses based upon the human brightness perception phenomena (thus excluding two identified spaces, #004 and #006).

3.2 Point in Time Metrics

In general, looking at correlation coefficients of students' assessments, point-in-time simulation results showed considerably stronger correlations with students' subjective responses than did annual simulation results. This finding confirms the previous work (Nezamdoost and Van Den Wymelenberg, 2015) that showed point-in-time simulation results had less average percent of difference between student daylight area evaluations than did annual simulation results.

Moreover, as noted in section 2.3.1, given the lack of consensus around annual daylight metrics illuminance thresholds a wide varied range of illuminance indicators (ranging from 50-500 Lux) were chosen and examined in the 24 study spaces in order to understand the most correlated threshold based on students' qualitative assessments for point-in-time evaluations.

Six major qualitative questions were addressed in this correlation study: A1 (I enjoy being in this room), B1 (I can work happily in this room with all the electric lights turned off), C1 (The daylight in this room is sufficient), D1 (The daylight in this room is not too bright), E1 (I like the daylight Uniformity) and I1 (There is no glare from direct sun penetration).

Table 2-6 Correlations of point in time illuminance indicators with major questions

% of Area > X Lux	Group	A1	B1	C1	D1	E1	I1
50 Lux	1	0.443	0.464	0.534	0.091	0.364	0.003
	2	0.445	0.461	0.535	0.078	0.369	0.002
75 Lux	1	0.491	0.514	0.596	0.099	0.428	0.004
	2	0.494	0.513	0.600	0.086	0.436	0.003
100 Lux	1	0.526	0.556	0.651	0.104	0.474	0.003
	2	0.531	0.555	0.657	0.090	0.484	0.002
125 Lux	1	0.553	0.582	0.694	0.110	0.510	0.002
	2	0.558	0.581	0.702	0.095	0.522	0.001
150 Lux	1	0.560	0.581	0.704	0.104	0.519	0.001
	2	0.570	0.588	0.718	0.097	0.538	0.001
175 Lux	1	0.535	0.549	0.676	0.087	0.497	0.001
	2	0.573	0.591	0.728	0.096	0.545	0.001
200 Lux	1	0.479	0.489	0.614	0.064	0.454	0.000
	2	0.567	0.587	0.728	0.093	0.544	0.000
250 Lux	1	0.423	0.436	0.565	0.046	0.417	0.000
	2	0.546	0.585	0.732	0.085	0.533	0.000
300 Lux	1	0.402	0.409	0.543	0.037	0.394	0.001
	2	0.540	0.559	0.723	0.078	0.526	0.000
350 Lux	1	0.374	0.368	0.510	0.026	0.361	0.003
	2	0.529	0.533	0.712	0.066	0.506	0.001
400 Lux	1	0.353	0.338	0.485	0.019	0.335	0.007
	2	0.509	0.501	0.691	0.055	0.478	0.004
450 Lux	1	0.338	0.316	0.468	0.015	0.314	0.009
	2	0.488	0.469	0.665	0.047	0.447	0.006
500 Lux	1	0.329	0.293	0.431	0.012	0.290	0.011
	2	0.467	0.426	0.638	0.041	0.421	0.007

As shown in table 2-6, Questions D1 and I1 (daylight excessiveness) achieved overall very low R^2 values in comparison to other questions. The poor performance of questions D1

and I1 would seem to be associated with ability of people to evaluate daylight sufficiency better than daylight excessiveness.

Looking at table 2-6 in Group 1 (all study spaces), the most promising indicators in predicting view quality (A1), daylight sufficiency (B1 and C1), and daylight uniformity (E1) are *125 and 150 Lux* together. While in Group 2 (those spaces with less potential for occupant visual brightness perception to impacted results) the percent floor above higher illuminances (*175 Lux, 200Lux, 250Lux and arguably 300Lux*) correlate more strongly with daylight sufficiency questionnaire items.

As was expected based upon previous work (Nezamdoost and Van Den Wymelenberg, 2015) the two groups showed statistically significant differences, and the average correlation values improved from $r^2=0.44$ to $r^2=0.60$, specifically at high illuminance levels. To illustrate this effect, two categories of study spaces were plotted in figure 2-8 based on question C1, where the horizontal scale is the percent of floor area above 300 Lux compared with the Likert scores along vertical axis. The blue circles represent all study spaces while red circles are only spaces that are less likely to have a substantial effect based upon Occupant Visual Brightness Perception

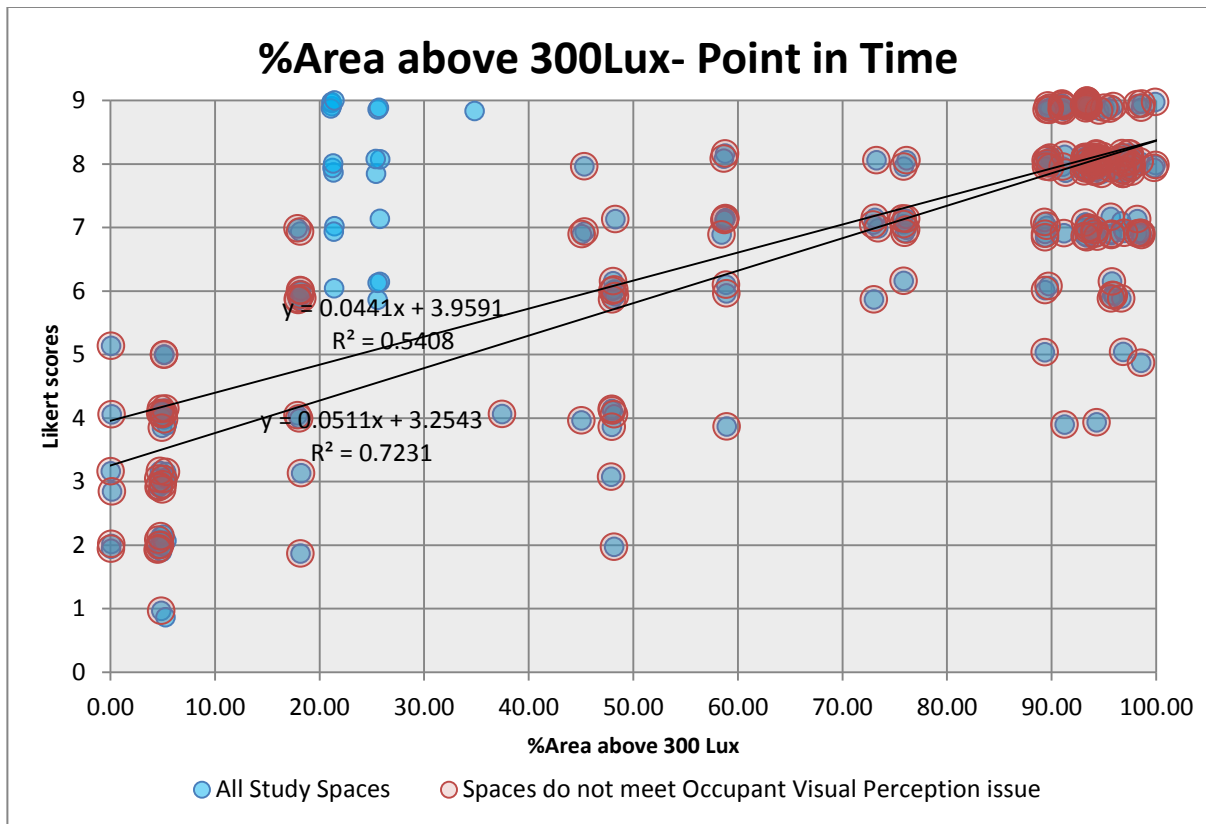


Figure 2-8 Comparing point-in-time correlation results of percent area above 300Lux and students' responses in two categories: All study spaces (blue), and study spaces excluding those likely to be impacted most by Occupant Visual Brightness Perception (red)

Finally, the translation of the point-in-time simulation results into occupants' preferred values is plotted in figure 2-9. This figure takes point-in-time simulation output, organizes it in a two-way table, percent area versus illuminance indicator thresholds, and color-codes it by students' responses (Likert scores 1-9) to question C1 "The daylight in this room is sufficient". Accordingly, students' scores were classified into three categories: Preferred (Likert scores 7-9), Acceptable/Nominal (Likert scores 5-6) and unacceptable (Likert scores 1-4). Then, linear trendlines were plotted to show the proportional relationship between acceptable range of percent area and illuminance level based on students' evaluations. The blue trendline interprets the boundary between the unacceptable and acceptable ranges, meaning that a study space would not be designated as "acceptably" daylit if less than the

specified percent area was achieved, as shown by the values below the blue trendline, when referencing a particular illuminance threshold. The purple trendline shows the transition between the “acceptable” and “preferred” range of percent area for each illuminance threshold. In other words, an analysis area will be rated as preferred, if it meets or exceeds the area corresponding to the purple trendline when referencing each illuminance indicator threshold.

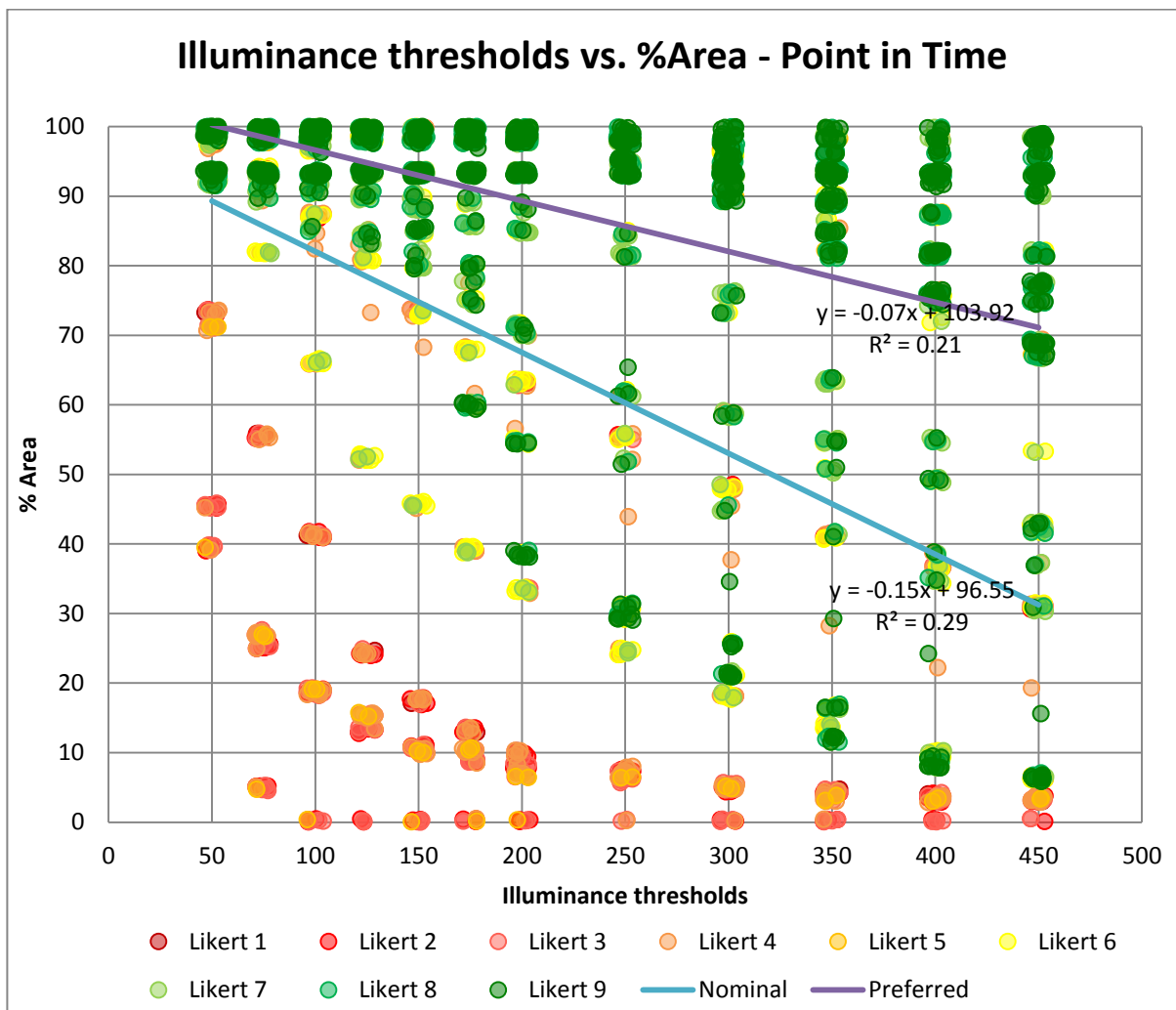


Figure 2-9 Comparing Point-in-time correlation results of percent area and illuminance thresholds color coded by students' responses (Likert scores 1-9) based on question C1

Table 2-7 shows the correlation coefficient results of six candidate indicators at the high level of illuminance (ranging 800 to 5000 lux) with six major questions, color-coded with strength of R^2 values. Again, Group 2 (those spaces with less potential for occupant visual brightness perception to impacted results) better matched with subjective responses rather than all study spaces (Group 1).

Looking at the table 2-7, very poor R^2 values in glare questions confirm the previous studies (HMG PIER 2012; Hescong and Van Den Wymelenberg, 2012) that there is not substantial evidence for an upper limit being defined. However, at high level of illumination, correlation values slightly increased based on question I “There is low probability of glare from direct sun penetration”; where the students’ visual discomfort peaked at 2000Lux; yet still were not very compelling ($R^2 = 0.1$).

Table 2-7 Correlation of point-in-time simulation results at high level of illuminance indicators with students’ evaluation

% of Area> X Lux	Group	A1	B1	C1	D1	E1	I 1
800 Lux	1	0.260	0.217	0.385	0.002	0.218	0.026
	2	0.354	0.306	0.513	0.013	0.294	0.022
1000 Lux	1	0.219	0.175	0.344	0.000	0.173	0.053
	2	0.292	0.243	0.447	0.004	0.230	0.049
1500 Lux	1	0.134	0.101	0.252	0.005	0.094	0.094
	2	0.175	0.139	0.317	0.001	0.123	0.091
2000 Lux	1	0.097	0.071	0.208	0.010	0.065	0.101
	2	0.126	0.097	0.258	0.004	0.085	0.099
3000 Lux	1	0.116	0.094	0.165	0.003	0.095	0.040
	2	0.138	0.115	0.194	0.008	0.112	0.038
5000 Lux	1	0.116	0.090	0.167	0.006	0.087	0.025
	2	0.125	0.097	0.179	0.007	0.093	0.025

3.3 Annual Metrics

Sensitivity studies were also conducted in annual simulations to determine which illuminance indicator thresholds (ranging from 100-5000 Lux) best predict students' subjective responses to questions pertaining to the entire year. Table 2-8 shows correlation values of six major questions (A "I enjoy being in this room", B "I can work happily in this room with all the electric lights turned off", C "The daylight in this room is always sufficient", D "The daylight in this room is never too bright", E "I like the daylight uniformity", and I "There is low probability of glare from direct sun penetration") with spatial Daylight Autonomy using a range of lux levels (100-5000), and using 50% of the time between 8AM and 6PM as the time threshold, in two categories (Group 1 and 2 – Refer section 3-1).

As shown in table 2-8, by excluding those spaces demonstrating characteristics consistent with occupant visual brightness perception issue, average correlation values significantly improved from $r^2=0.21$ to $r^2=0.43$ in annual simulation results (almost doubled).

Looking at table 2-8, the strongest correlation values in all study spaces were reported in range of 100 lux to 300 lux. However, high r^2 value for the low illuminance thresholds could not be reliable enough due to not normal distribution data. According to the Pearson R correlation, both variables should be normally distributed (Daniel W.W. 1990 and Kowalski, D. J. 1972). To illustrate this issue, two correlation scatterplots in 100 lux and 300 lux were plotted in figure 2-10 based on question C "The daylight in this room is always sufficient", where the horizontal axis is percent area above 100 lux or 300 lux compared with the Likert scores along vertical axis. As it was expected, in low illuminance level (100 lux) most answers were provided in one little quadrant of the field (saturated) and a few answers where

there is no stimulus (black room) and the line between the two chunks of data makes for a stronger r^2 value.

It was found that in high level of illumination, R^2 values gradually decreased (negative trend) and no upper limit can be found in daylight sufficiency and view quality questions. It means students feel visually comfortable in low level of illuminance than bright conditions. Although the findings support the previous researches (HMG PIER 2012; Heschong and Van Den Wymelenberg, 2012) that no upper limits to annual daylight autonomy values were found, but at high level of illumination (sensor*hours) an increase in correlation values were reported based on question I “There is low probability of glare from direct sun penetration”; where the students’ dissatisfaction from brightness increased at 1000Lux and peaked at 3000Lux; yet still were not very compelling ($R^2 = 0.09$).

Table 2-8 Correlation results for spatial Daylight Autonomy with Blinds Open

Dependant	Group	A2	B2	C2	D2	E2	I 2
sDA100/50%	1	0.320	0.283	0.278	0.016	0.245	0.009
	2	0.566	0.511	0.505	0.025	0.484	0.018
sDA125/50%	1	0.284	0.258	0.249	0.015	0.220	0.010
	2	0.563	0.521	0.507	0.026	0.491	0.022
sDA150/50%	1	0.291	0.268	0.258	0.015	0.231	0.011
	2	0.556	0.519	0.503	0.026	0.493	0.022
sDA175/50%	1	0.294	0.274	0.262	0.014	0.237	0.012
	2	0.544	0.516	0.497	0.024	0.489	0.024
sDA200/50%	1	0.289	0.277	0.264	0.013	0.241	0.012
	2	0.522	0.510	0.489	0.022	0.482	0.025
sDA250/50%	1	0.266	0.263	0.253	0.009	0.233	0.011
	2	0.488	0.498	0.480	0.020	0.468	0.023
sDA300/50%	1	0.206	0.212	0.206	0.003	0.192	0.009
	2	0.428	0.462	0.449	0.014	0.432	0.019
sDA350/50%	1	0.178	0.192	0.187	0.001	0.174	0.007
	2	0.376	0.423	0.412	0.009	0.392	0.016
sDA400/50%	1	0.156	0.175	0.173	0.000	0.157	0.005
	2	0.331	0.386	0.378	0.005	0.351	0.012
sDA500/50%	1	0.136	0.151	0.153	0.000	0.131	0.001
	2	0.293	0.342	0.342	0.001	0.301	0.005
sDA600/50%	1	0.129	0.138	0.146	0.002	0.112	0.000
	2	0.267	0.302	0.312	0.000	0.250	0.000
sDA700/50%	1	0.127	0.127	0.138	0.004	0.098	0.001
	2	0.252	0.269	0.286	0.001	0.215	0.001
sDA800/50%	1	0.116	0.111	0.126	0.006	0.084	0.004
	2	0.220	0.228	0.249	0.002	0.179	0.004
sDA1000/50%	1	0.072	0.075	0.076	0.028	0.045	0.022
	2	0.133	0.145	0.146	0.022	0.096	0.024
sDA2000/50%	1	0.029	0.030	0.040	0.029	0.015	0.023
	2	0.050	0.055	0.070	0.026	0.032	0.025
sDA3000/50%	1	0.000	0.000	0.003	0.089	0.002	0.097
	2	0.000	0.002	0.007	0.092	0.001	0.111
sDA5000/50%	1	0.001	0.000	0.001	0.068	0.004	0.078
	2	0.000	0.000	0.003	0.071	0.002	0.088

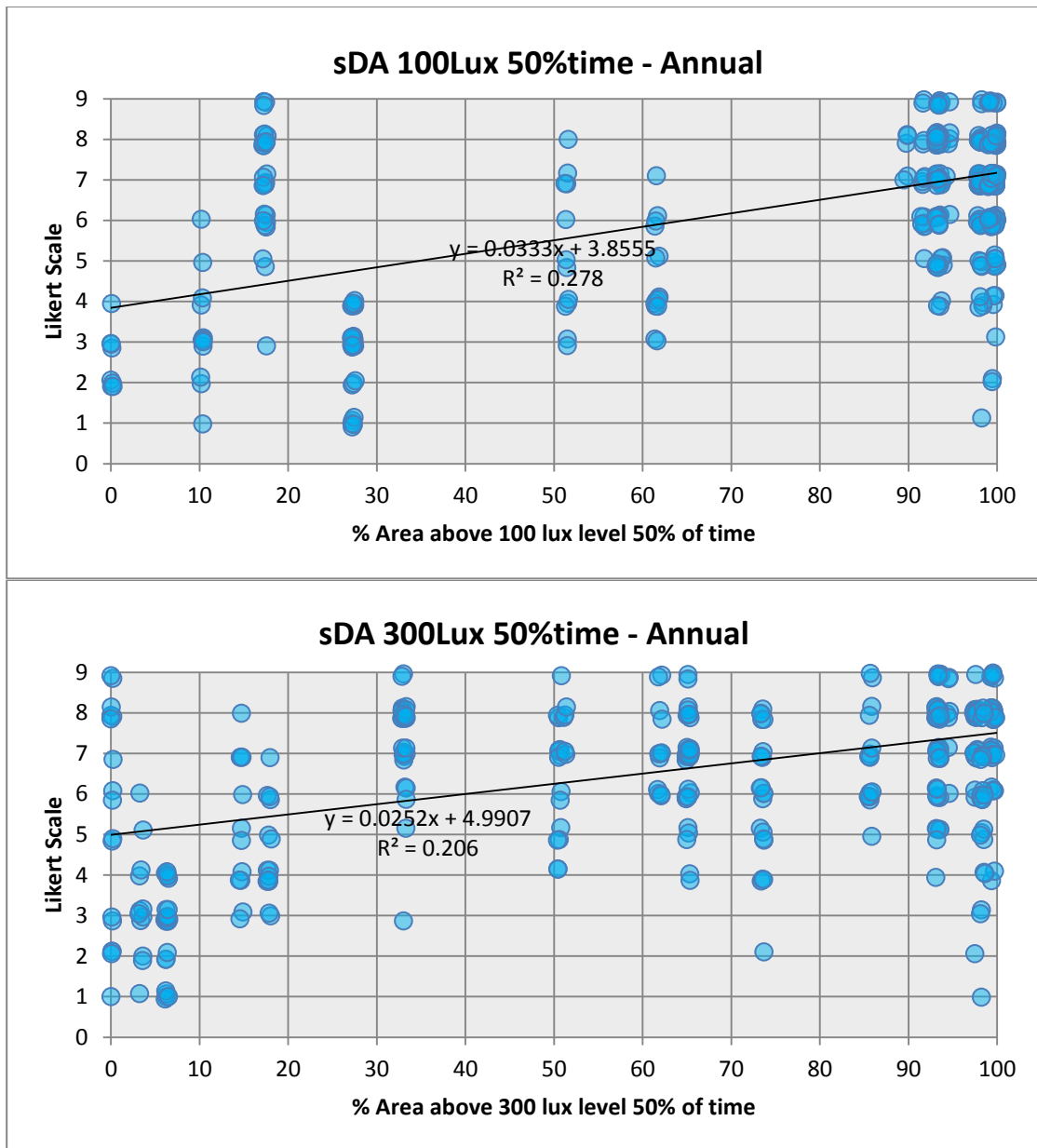


Figure 2-10 Comparing annual correlation results of percent area above 100 lux and 300Lux (top to bottom respectively) and students' responses to question C, in all study spaces (Group 1)

Similar to point-in-time simulation, in figure 2-11, annual simulation result is illustrated in a two-way table, percent area versus illuminance indicator thresholds, and is color-coded by students' responses (Likert scale 1-9) to question C2 "The daylight in this room is always sufficient". Again, students' assessments were divided into three groups based upon Likert scores: Preferred (Likert scores 7-9), Acceptable/Nominal (Likert scores 5-

6) and unacceptable (Likert scores 1-4). Then linear trendlines were plotted to show the proportional relationship between acceptable range of percent area and illuminance level based on students' evaluations. The blue trendline interprets the boundary between the unacceptable and acceptable ranges, meaning that a study space would not be designated as daylit if less than the specified percent area, as shown according to the blue trendline, was achieved when referencing a particular illuminance threshold. The purple trendline shows the transition between the acceptable and preferred range of percent area for each illuminance threshold. In other words, an analysis area will be rated preferred, if it meets or exceeds the purple trendline when referencing each illuminance indicator threshold.

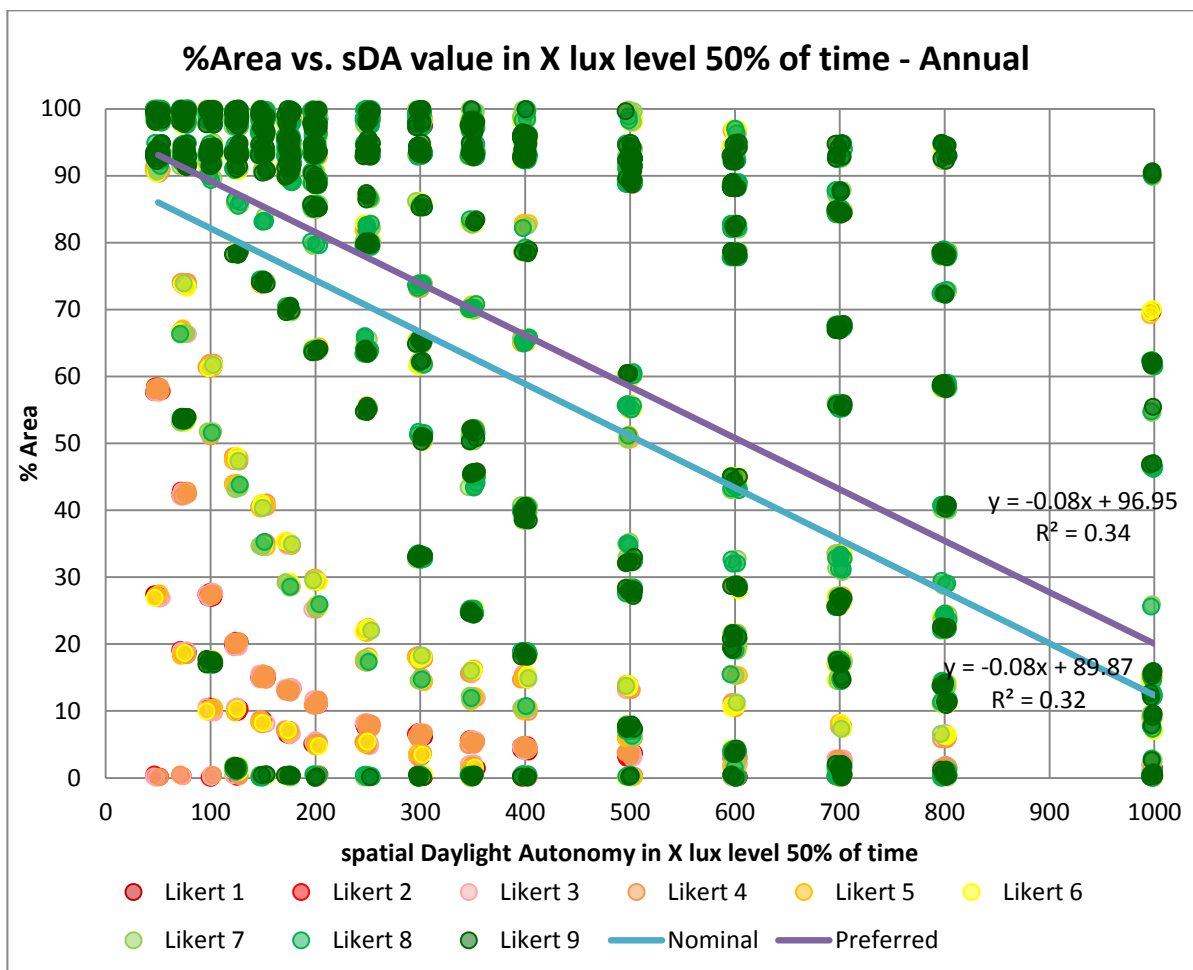


Figure 2-11 Comparing annual correlation results of percent area and spatial daylight autonomy in different illuminance levels color coded by students' responses (Likert scores 1-9) based on question C2

The LM-83 defined parameters for ASE calculation produces a value that represents the percent of an analysis area that exceeds 1000 Lux of “direct sunlight” illuminance for more than 250 hours per year. According to LM-83, preliminary data suggest that if the ASE exceeds 10%, the space will be judged to have unsatisfactory visual comfort. ASE is considered as one of two modeling compliance paths for Indoor Environmental Quality (EQ) Daylight Credit in recently updated version of LEED (V4). According to LEED V4, acceptable spaces are those with at least 55% spatial Daylight Autonomy_{300/50%} (sDA_{300/50%}) and no more 10% annual sunlight exposure_{1000,250} (ASE_{1000,250}). Preliminary analysis suggests that this ASE criteria may be too restrictive and may result in seemingly well-daylit and visually comfortable spaces not achieving the metric. Nezamdoost and Van Den Wymelenberg (2015) examined LEED V4 criteria for the Indoor Environmental Quality (EQ) Daylight Credit on 22 spaces, but only eight spaces passed. Fourteen of the 22 spaces met the sDA (LM-83) portion of the LEED V4 Indoor Environmental Quality (EQ) Daylight Credit, meaning that 6 of the 14 failed due to the ASE 10% threshold criteria required by LEED V4.

Therefore, a case study analysis of 19 study spaces was conducted and compared several alternate performance criteria. We studied alternate *nHours* (250, 300, 600 and 900 hours) criteria as proposed by HMG-PIER Review 2012, as well as the maximum number of hours that any one single point in entire room received of direct sunlight (simulated 1000 Lux). Figure 2-12 illustrates this case study, whereas the primary vertical axis (left) is the percent area above 1000 Lux and the solid colored lines represent alternate numbers of hours; and whereas, the secondary vertical axis (right) is ASE max (maximum number of hours that one single point in entire room achieved direct sunlight) represented by the orange dashed line.

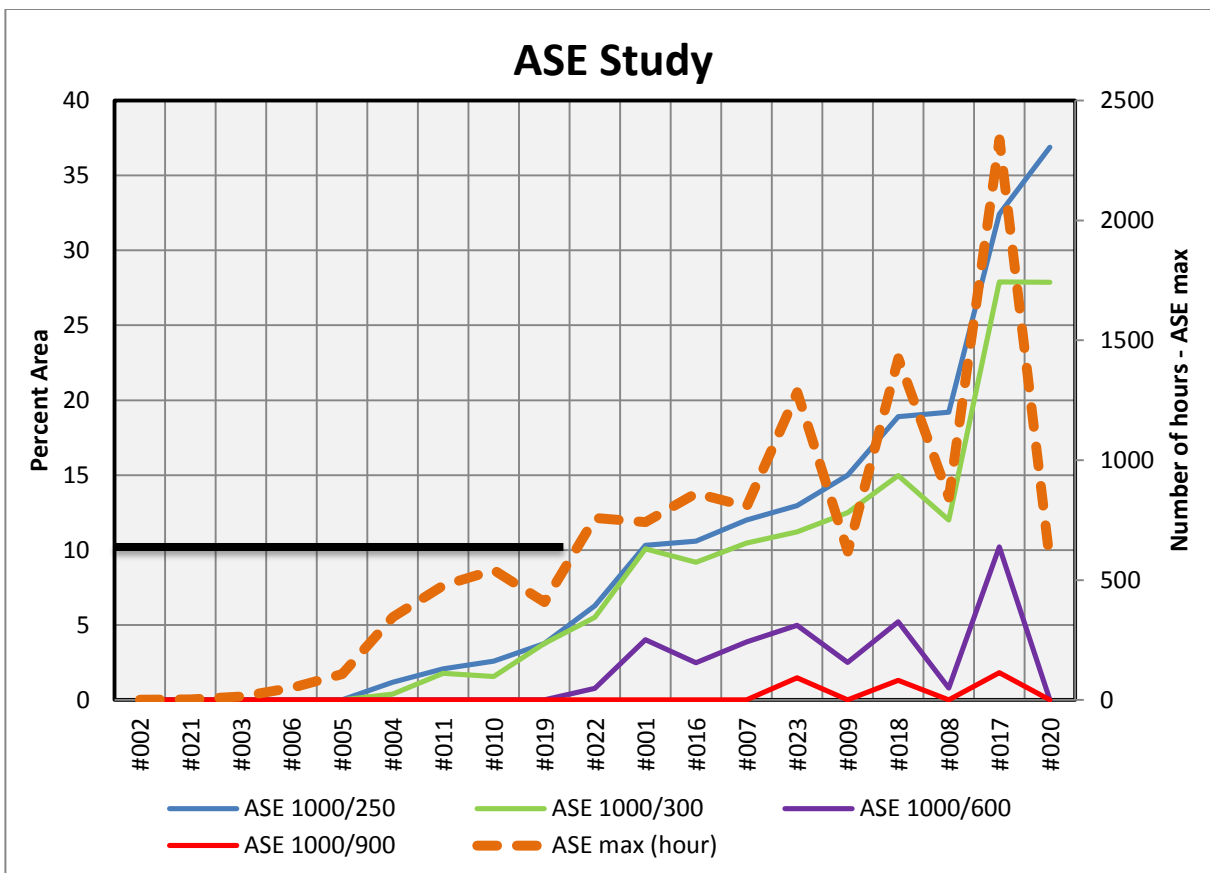


Figure 2-12 Comparing Annual Sunlight Exposure (ASE) in 250, 300, 600 and 900 nHours indicators plus ASE max; ordered by ASE_{1000Lux250hours}; the red horizontal line pertains to the left axis and indicates the current LM-83 preliminary criteria (1000/250)

Looking at figure 2-12, at 250 and 300 hours exceeding 1000 Lux direct sunlight, almost half of study spaces failed, having results higher than 10%. Conversely, the values recorded at 900 hours are too unresponsive to the amount of sunlight - mostly hovering at or just about zero % of the space, and therefore, it does not provide useful information. Interestingly, the 600-hour values show more fluctuation and show variation in rank order as compared to ASE 1000/250. The same can be said for the ASE Max line (orange dashed line, right axis).

Correlational analyses were run and illustrated in table 2-9, using annual simulation results comparing the number of hours (nHours) exceeding 1000 lux and students' responses

to visual comfort questions (D2 “The daylight in this room is never too bright”, I2 “There is low probability of glare from direct sun penetration”, J2 “I am able to do my work here without any problems from daylight induced glare”, K2 “The computer screens are legible and free of veiling reflections” and L2 “There is low probability of glare from daylight apertures”). ASE 1000Lux at 600 hours shows slight improvement over ASE Max and over 300 hours. The IES LM-83 preliminary criteria may need more nuance, but given the greater diversity in results for ASE 250, ASE 300 and ASE Max, one of these indicator values is likely to produce the most discernment in results. However, it appears as though ASE 1000 Lux 250 hours at 10% threshold warrants refinement. Moreover, further investigation about the order changes in a few spaces (8, 9, and 20 – east and west facing exposures) is warranted.

Table 2-9 Correlation plot of ASE metric in four nHour indicators versus glare questions

	D2	I 2	J2	K2	L2
ASE.1000Lux250hr	0.075	0.167	0.048	0.027	0.070
ASE.1000Lux300hr	0.100	0.203	0.077	0.051	0.096
ASE.1000Lux600hr	0.105	0.226	0.128	0.113	0.107
ASE.1000Lux900hr	0.065	0.156	0.075	0.062	0.073
ASE.max	0.112	0.205	0.118	0.099	0.105

3.4 Blinds Operation

In order to examine performance of three leading manual blind control patterns (Blindswitch-A, Blindswitch-B and LM83) in detail, correlational analyses were run between students’ subjective responses and annual average of daily number of blind movements (NBM), annual average of daily rate of change (ROC) and annual average percent of blind occlusion. ROC is calculated to determine how many blinds move per day, that is, whether a particular blind either engages or retracts at least one time per day. However, ROC does not take into account how often a particular blind changes per day. Therefore, NBM is required,

as it shows the ratio of the total number of blind movements per day to the total number of blinds that moved (at least once) per day per façade (Dyke et al. 2015).

Table 2-10 shows correlation results of NBM and ROC and percent of blind occlusion of three current candidate manual blind control algorithms (Blindswitch-A, Blindswitch-B and LM83). Among blind algorithms, LM-83 shows highest R^2 values, specifically in question H “I am happy with how the blinds/curtains can be operated”. In other words, students’ feeling of daylight sufficiency, daylight excessiveness and blind position are more closely correlated to the annual daylight results derived with the algorithm used by LM-83. This could be because it is difficult for students to predict annual blind use patterns, and LM-83 generally has the least blind occlusion. With most other cases, the adjustments in the R^2 values are relatively small. For example, Blindswitch-B shows a slightly better fit to question G (I am able to do my work here without any problems from daylight induced glare), but it is difficult to claim this as a meaningful improvement.

Table 2-10 Correlation results of NBM, ROC and percent of blind occlusion of three manual blind control patterns with four major questions

NBM	C2	D2	G2	H2
BSA	0.002	0.014	0.006	0.009
BSB	0.018	0.040	0.139	0.061
LM83	0.097	0.091	0.015	0.104
ROC				
BSA	0.008	0.002	0.015	0.000
BSB	0.009	0.018	0.069	0.023
LM83	0.046	0.051	0.008	0.042
% occlusion				
BSA	0.006	0.080	0.067	0.087
BSB	0.016	0.049	0.123	0.079
LM83	0.084	0.198	0.071	0.227

C2- The daylight in this room is always sufficient.

D2- The daylight in this room is never too bright.

G2- I am able to do my work here without any problems from daylight induced glare.

H2- I am happy with how the blinds/curtains can be operated.

3.4.1 Relationship between sDA and Blind Occlusion

Higher blind occlusion can be thought of as a higher possibility that windows are covered by blinds and would logically result in less daylight penetration into the space. Consequently, a higher percentage of blind occlusion should decrease spatial Daylight Autonomy (sDA). But surprisingly, comparing sDA and blind occlusion in a few study spaces did not follow this logic. Figure 2-13 shows a sample of simulation results in study space #017, where the dark blue line with diamonds shows the values of blind occlusion for three manual blind control algorithms (Blindswitch-A, Blindswitch-B and LM-83) and the dark green dashed line with triangles shows the sDA value of 300 Lux for 50% of time. It can be seen that in this case, Blindswitch-B has the lowest blind occlusion, so it was expected to have the highest sDA among the three algorithms, but in fact, it is the lowest.

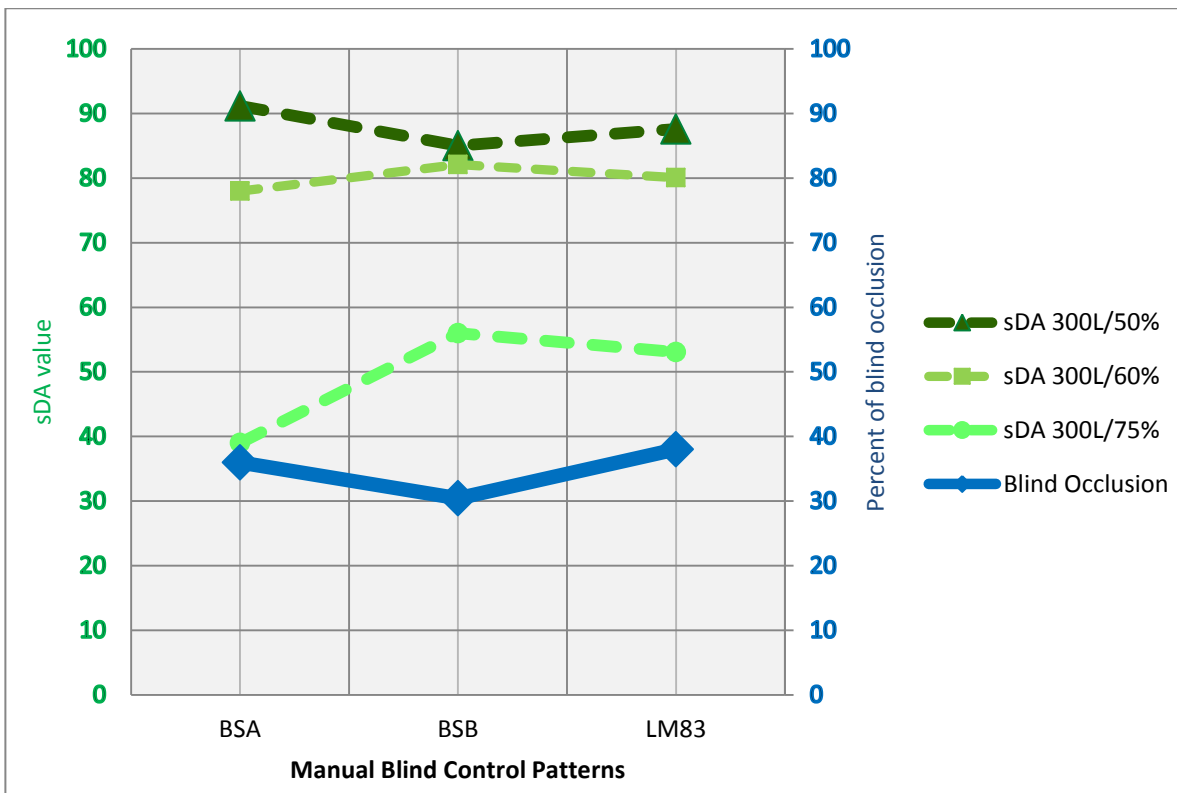


Figure 2-13 Comparing percent of blind occlusion with sDA values in different time thresholds in study space #017

Therefore, the $sDA_{300Lux/50\%}$ values and blind occlusion percentages of all of the study spaces were calculated and compared. Surprisingly, of the 12 spaces with blinds installed, six spaces displayed the same unexpected result. To examine this further, two more indicators of time were analyzed: sDA_{300Lux} in 60% Time and sDA_{300Lux} in 75% Time. By examining the 75% time threshold a more logical pattern emerged between blind occlusion and sDA . This suggests that while Blindswitch-B resulted in lower blind occlusion, and thus, blinds were open more often than for Blindswitch-A or LM-83, the blinds were not open for enough more hours such that the difference in hours with more daylight admitted to the space was detectable by 50% time indicator value.

Floor plan iso-lux plots illustrated in figure 2-14, reveal the performance of three manual blind algorithms on the distribution of daylight in one of the study spaces with the % time issue mentioned above. It is a south facing space with 10 big window groups and ASE equals to 32.48. The green and orange zones together represent the area above $DA_{300Lux/50\%}$ of time, while the orange zone alone represents the percent floor above $DA_{300Lux/75\%}$ of time. In this study space, Blindswitch-B produces the lowest blind occlusion of the three manual blind algorithms, but it can easily be seen that the green and yellow areas are not higher than other algorithms; while, by looking only at the green area in three algorithms, the highest proportion of daylit area belongs to Blindswitch-B, which matches expectations based upon the blind occlusion percentages.

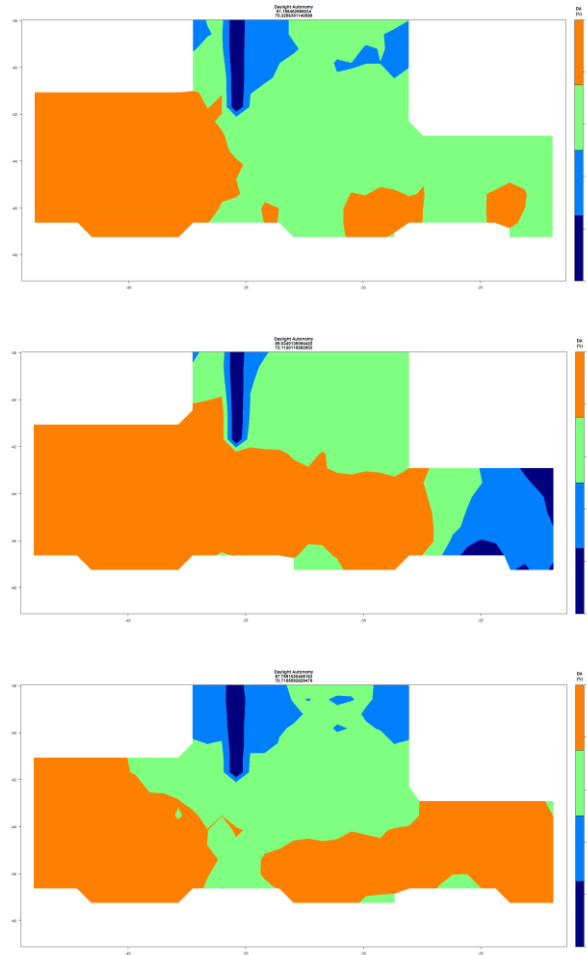


Figure 2-14 Comparing floor plan plots of 50% (Green and orange) and 75% (Orange) of time thresholds in three manual blind algorithms (From top to bottom: Blindswitch-A, Blindswitch-B and LM83 respectively) in study space #017

3.5 Comparing spatial continuous Daylight Autonomy and spatial Daylight Autonomy

Continuous Daylight Autonomy (cDA) is a variation on Daylight Autonomy that awards partial credit for grid-point-hours less than the target threshold. Although cDA can be said to have greater discernment in spaces with lower illuminances and better sensitivity to small changes, it also suffers from less discernment at higher illuminances. Furthermore, it can be more difficult to interpret differences when comparing two potential designs since two options could potentially have similar cDA values, or both change the cDA by 10%, but it's

not clear whether that is due to 300 lux for 10% of the time, or 30 lux 100% of the time.

Figure 2-15 is a compelling representation of the strength and limits of the spatial

$cDA_{300Lux/50\% \text{ time}}$, $\text{spatial } cDA_{500Lux/50\% \text{ time}}$ and $sDA_{300Lux/50\% \text{ time}}$ in both blinds open and operated using LM-83 blind logic.

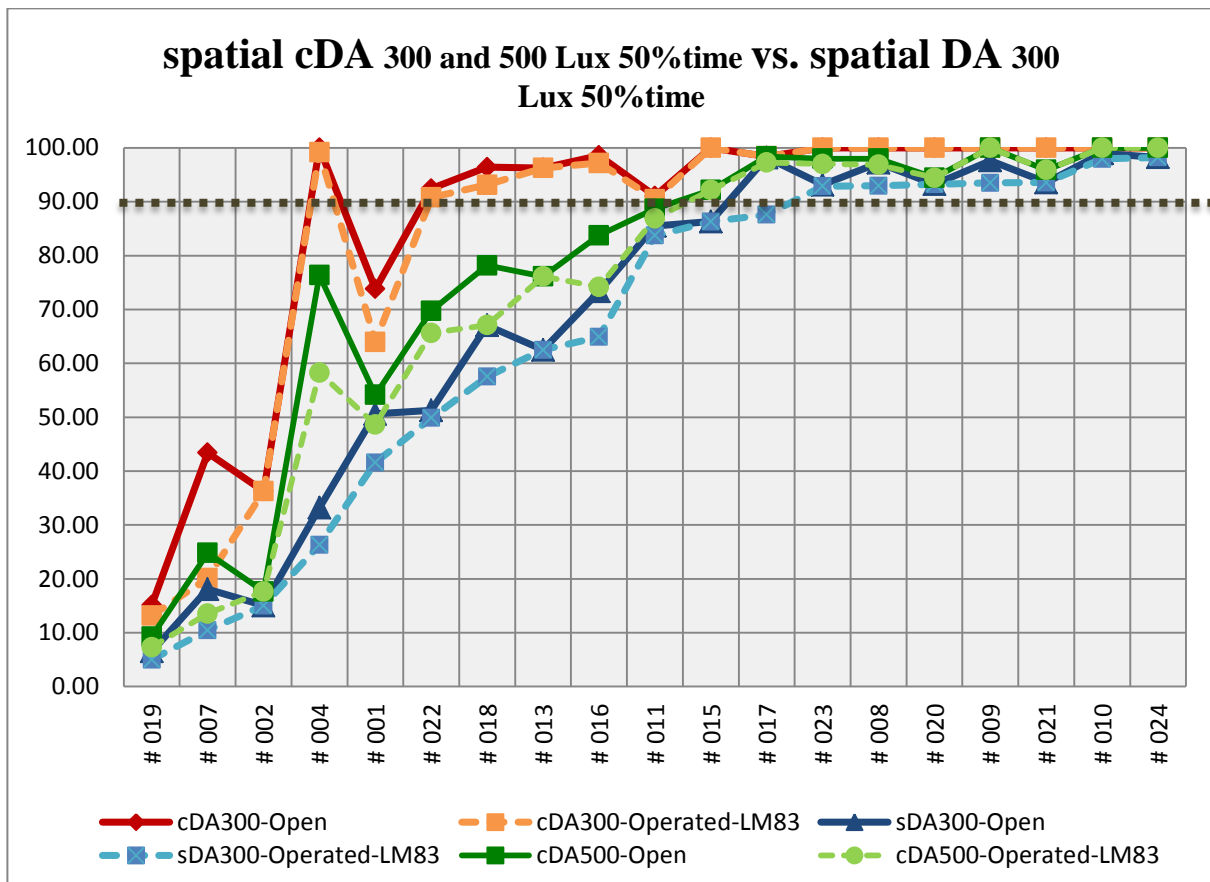


Figure 2-15 Comparison plot of spatial cDA 300Lux/50%, cDA500Lux/50% and spatial DA 300Lux/50% with blinds open and operated (LM83)

As expected, high values for spatial $cDA_{300Lux/50\% \text{ time}}$ (Blinds open) were reported. In 15 out of 19 spaces, spatial $cDA_{300Lux/50\% \text{ time}}$ is above 90%, which confirms the idea that average daylight spaces report high results for cDA making it more difficult to differentiate between spaces or design options of well daylight spaces.

Figure 2-16 illustrates DA and cDA sensor plots in 300 and 500 lux and 50% of the time with blinds open and operated in study space #004. Generally, daylight interpretation in

all three cases is almost the same, due to similar shapes of contours. sDA_{300Lux/50% time} plot reveals more information in comparison to cDA_{300Lux/50% time} and cDA_{500Lux/50% time} plots, for at least two reasons: (1) The contour lines in the sDA plot spread out from 0% to 100% and displays both low light levels and high light levels which could be helpful to the designers. (2) The overall distribution patterns of contour lines are much wider in the in cDA plots, thus values do not have enough variation to provide discernment.

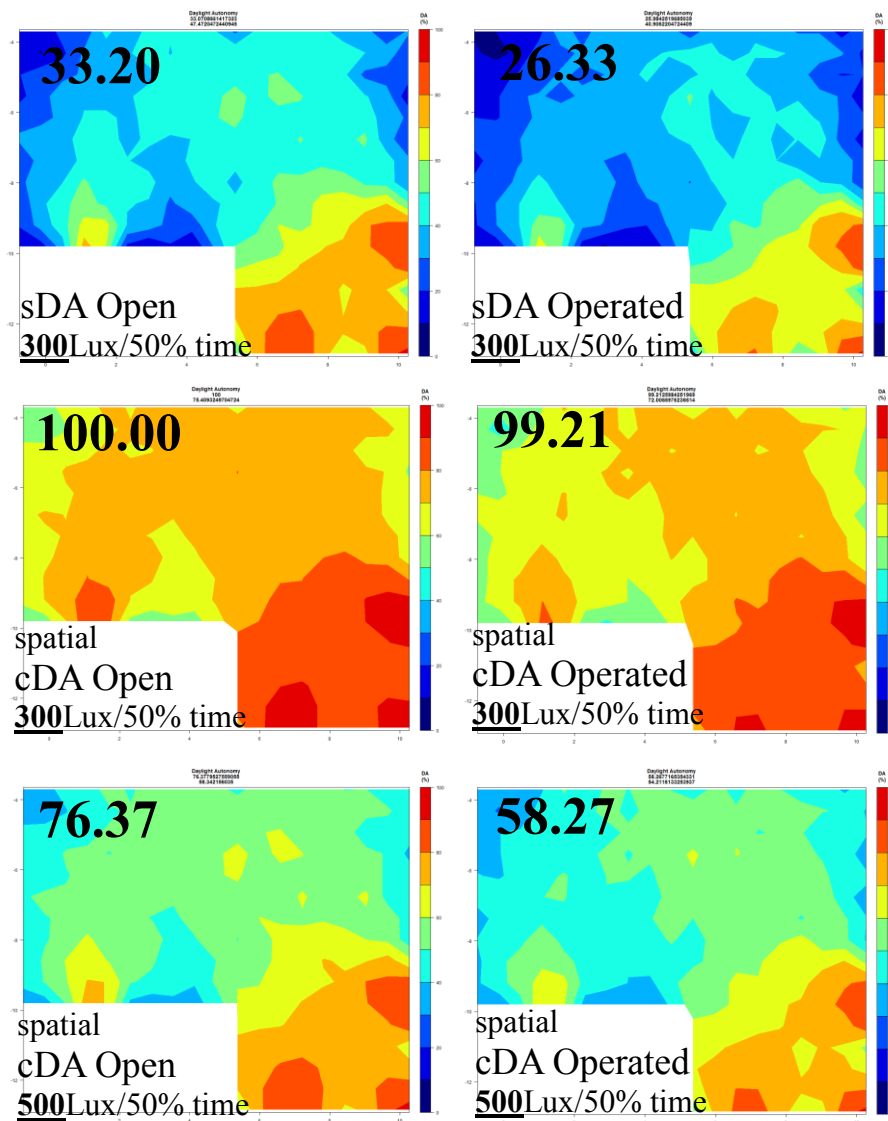


Figure 2-16 Floor plan plots of spatial DA 300Lux/50%, spatial cDA 300Lux/50% and spatial cDA 500Lux/50% with blinds open and operated (LM83) in space #004

Lastly, correlations were run for both spatial DA and spatial cDA in 300 Lux, 50% of time (8AM-6PM during whole year) versus students' subjective responses to daylight sufficiency questions, and shown in table 2-11. Accordingly, spatial cDA shows slightly better fit to students' expectations than spatial DA, which is not a big surprise because according to the Pearson *R* correlation, both variables should be normally distributed (Daniel W.W. 1990 and Kowalski, D. J. 1972), and based on figure 3-10, the spatial cDA values in this study are mostly reported above 90%; so there is a possibility to have not normal distribution data.

Table 2-11 Correlation plot of spatial cDA 300Lux/50% and spatial DA 300Lux/50% with blinds open versus students' subjective responses to daylight sufficiency questions

	B2	C2	E2
sDA.Open.300Lux.50percent.time	0.456	0.436	0.417
cDA.Open.300Lux.50percent.time	0.502	0.481	0.469

To illustrate this point, correlation of annual simulation results in two variations of daylight autonomy, spatial cDA (red squares) and spatial DA (blue circles), with students' subjective responses (Likert scores) to question BC "I can work happily in this room with all the electric lights turned off - The daylight in this room is always sufficient" were plotted in figure 2-17, where the horizontal scale is the percent area above 300 Lux during 50% of occupied hours in entire year, compared to the Likert scores along the vertical axis. It can be seen that the red squares are mostly clustered together on high percentages, and are not normally distributed.

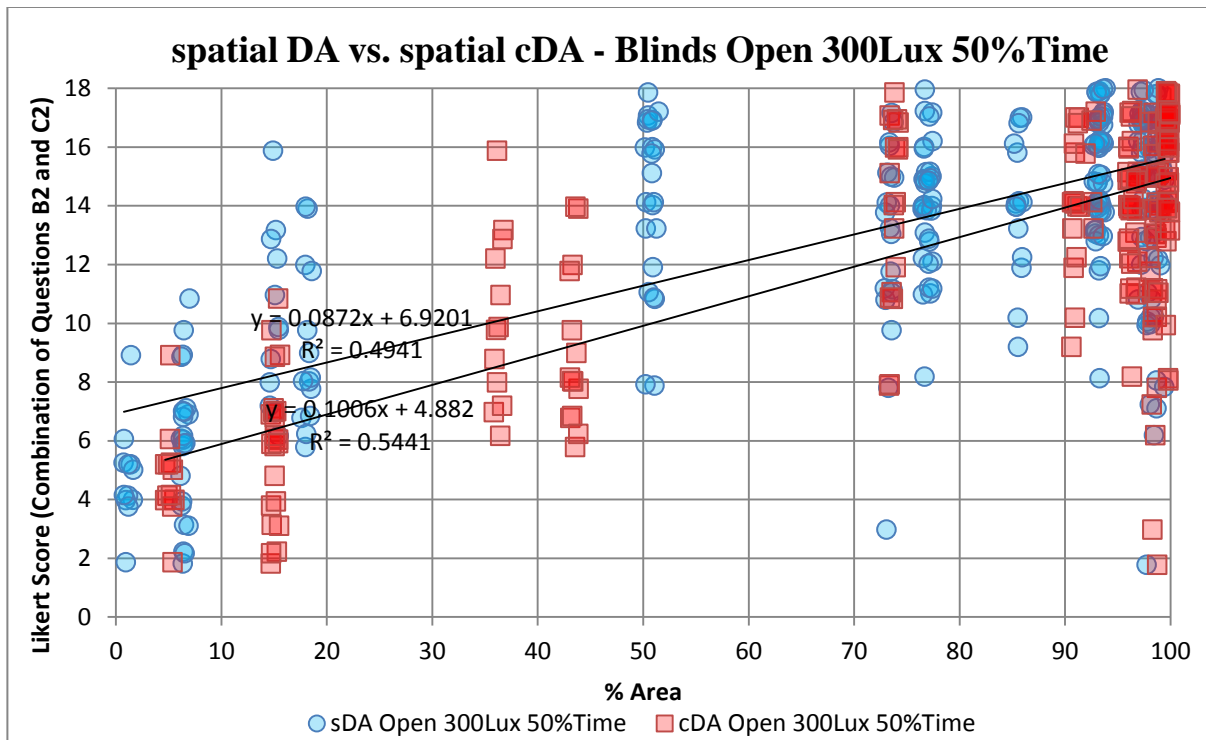


Figure 2-17 Comparing annual correlation results of spatial cDA 300Lux/50% and spatial DA 300Lux/50% with blinds open versus students' subjective responses to question BC

4. Discussion and Conclusion

The research plan was conducted to understand how well alternative point-in-time illuminance thresholds and annual simulated daylight results for daylight sufficiency and excessiveness correlate with students' qualitative assessments within 24 study spaces.

The strongest correlations of annual simulation results to students' qualitative assessments were reported in range of sDA100Lux/50% to sDA300Lux/50%; however choosing low illuminance thresholds are not statistically reliable due to not normally distributed data. According to the Pearson R correlation, both variables should be normally distributed (Daniel W.W. 1990 and Kowalski, D. J. 1972), but scatter plots in low illuminance thresholds revealed that the results were clustered together, i.e. the median is too close to the maximum value and the sample is not normally distributed.

It was found that a moderating variable defined as “Occupant Visual Brightness Perception” had statistically significant impact on students’ responses. By excluding those spaces with high potential for occupant visual brightness perception to impacted results, average correlation values improved from $r^2=0.44$ to $r^2=0.60$ in point-in-time, and from $r^2=0.21$ to $r^2=0.43$ in annual simulation results, specifically at illuminance thresholds greater than 250Lux. The reason it shows up more at higher illuminances is because at lower illuminance thresholds, spaces are more likely to saturate the low threshold. At higher illuminance levels, spaces are less likely to have large portions of the horizontal work plan achieve the higher thresholds, thus there is more opportunity for the vertical surface brightness perception to bias the students’ evaluations and result in differences between the subjective responses (Likert scores) and the simulated horizontal illuminance.

Additionally, strong correlation results between vertical surface brightness and daylight sufficiency questions confirms the significant impact of vertical surface brightness on occupant visual perception. Therefore, counting only on horizontal grid points is enough for accurate dynamic daylight simulations or not?

The paper has also provided evaluations using equivalent point-in-time daylighting results. The result section reveals that point-in-time simulation outcomes show considerably higher correlation values between students’ subjective responses than did annual simulation results. This is possibly due to the relatively better ability of people in evaluating spaces in the observation time than predicting whole year. The higher correlation for point-in-time results could open up a discussion to the question proposed by Van Den Wymelenberg (2014); is there an important difference between visual comfort research results obtained from naïve versus expert participants or occupants versus visitors?

For point-in-time analyses, the illuminance indicator value, 250 Lux has the strongest students' opinions about daylight sufficiency. On the other side, at high levels of daylight illumination, very poor R^2 values in glare questions confirm the previous studies (HMG PIER 2012; Heschong and Van Den Wymelenberg, 2012) that there is not substantial evidence for an upper limit being defined. However, at high level of illumination, correlation values slightly increased based on question I "There is low probability of glare from direct sun penetration"; where the students' visual discomfort peaked at 2000Lux in point-in-time analyses and 3000 Lux in annual analyses; yet still were not very compelling ($R^2 = 0.1$ and $R^2 = 0.09$ respectively).

Preliminary analysis suggests that the ASE 10% threshold criteria may be too restrictive and may result in seemingly well-daylit and visually comfortable spaces not achieving the metric. Therefore, a case study analysis of 19 study spaces was conducted and compared several alternate *nHours* (250, 300, 600 and 900 hours) criteria as proposed by HMG-PIER Review 2012, as well as the maximum number of hours that any one single point in entire room received of direct sunlight (simulated 1000 Lux).

At 250 and 300 hours exceeding 1000 Lux direct sunlight, almost half of study spaces failed, having results higher than 10%. While a few study spaces face northwest and the sun only comes in to small part of the space in the late afternoon and is not really a problem. Two of study spaces are reading rooms where people can choose where to sit. This suggests that perhaps temporal or space type sensitivity should be applied to these criteria.

Correlational analyses were also run. ASE 1000Lux at 600 hours shows slight improvement over ASE Max and over 300 hours. Given the greater diversity in results for ASE 250, ASE 300 and ASE Max, one of these indicator values is likely to produce the most

discernment in results. However, it appears as though ASE 1000 Lux 250 hours at 10% threshold warrants refinement.

Blind occlusion percentages were compared to $sDA_{300\text{Lux}/50\% \text{ time}}$ as a function of daylight availability study in spaces with blinds. Surprisingly it was found that those blind algorithms with higher blind occlusion did not show lower $sDA_{300\text{Lux}/50\% \text{ time}}$ values and vice versa. This paradox became bolder even in the sidelight spaces facing south and west (6 out of 12 study spaces). Examining other thresholds of time (60% and 75%), showed more expectable patterns in comparison to blind occlusion. In these spaces, it seems that the 50% time threshold does not show enough sensitivity to differences blind operation.

Two variations of daylight autonomy, spatial continuous $DA_{300\text{Lux}/50\% \text{ time}}$ and spatial $DA_{300\text{Lux}/50\% \text{ time}}$ were analyzed and compared. Generally, most of the study spaces produce very high values for spatial continuous $DA_{300\text{Lux}/50\% \text{ time}}$. In fact, 15 out of 19 spaces produce values higher than 90% of the floor area as “daylit” using this metric. This means that study spaces may produce very similar cDA values despite important performance differences making it a difficult metric to use for codes, reach standards, or design decision making. It is possible that a higher illuminance indicator value used with continuous DA could prove more useful at providing this important discernment ability.

However, some big research gaps can still be seen. Based on this study, still, the better understanding of annual-climate-based daylighting metrics is essential. It seems there is a need to conduct further validation studies of these annual daylighting metrics and criteria in order to increase designers’ confidence in their use and to help improve the science of annual-climate-based daylight simulation in the future. Future work should continue to update the

proposed illuminance thresholds based on additional human factors and post occupancy studies.

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CHAPTER 3

Annual Energy and Daylight Impacts of Manual and Automated Blind Algorithms

Manual and automated blind controls are typically not included in energy modelling and often not considered in daylight modelling. This is in part because there is no consensus in the research or practice communities about the way users operate manual blinds or override automated blinds. Recently the IES published LM-83 for annual daylight simulation and this document includes a preliminary manual blind use algorithm. A subsequent literature review proposed two alternate manual blind use algorithms. Blind control patterns (manual and automated) affect the energy consumption (interior lighting loads and space heating and cooling loads) of buildings. In order to become part of energy and daylight simulation best practices the range of annual energy and daylighting impacts associated with blind use must be understood, and a consensus-based manual algorithm achieved. This paper compares three leading candidate interior manual blind use algorithms and two interior/exterior automated blind control algorithms using a large open plan office floor plate within a high-rise building located in Boise, ID. Simulation results were integrated, using the RADIANCE lighting engine V.4.2.0 and thermal modelling program EnergyPlus V.8.3.0. Specifically, annual energy implications, blind average daily rate of change (ROC), average daily number of blind movements (NBM), blind occlusion (percent of windows with blinds closed), spatial daylight autonomy (sDA) and annual sunlight exposures (ASE), are compared for all five blind use algorithms. It is reported that annual lighting end-use energy consumption of the five strategies differed by approximately 24.2%, 8.3%, 5.8%, 29.2% and 8.3% using Blindswitch-A, -B, LM-83, Blind Manufacturer-Automated Algorithm A (BM-AAA) and Blind Manufacturer-Automated Algorithm B (BM-AAB) respectively, as compared to a baseline with blinds always retracted and with ideally functioning daylight sensing lighting controls. As expected, automated blind control algorithms, show lower average blind occlusion compared to manual blind use algorithms (except LM-83). The LM-83-based manual control algorithm and Blind Manufacturer-Automated Algorithm B (BM-AAB) have the lowest blind occlusion percentages of the three leading candidate manual blind use algorithms and two automated blind control algorithms when accounting for all facades. Subsequently, the

highest annual daylight sufficiency values (sDA) were recorded for Blind Manufacturer-Automated Algorithm B (BM-AAB) and LM-83, respectively. The highest NBM and ROC values were reported for Automated Algorithm A (BM-AAA) and Blindswitch-A for all facades, although Automated Algorithm B has 100% ROC due to the dawn/dusk privacy function during night-time hours. Automated Algorithm A (BM-AAA) and Blindswitch-A showed higher overall energy consumption when compared to the other three algorithms, having 5.6% and 4.01% higher whole building annual energy use than the baseline with lighting controls and blinds retracted. However, the real energy story is told by the variance in energy end uses for the alternate blind use algorithms as compared to the baseline (exceeding 10% difference), and to the “always closed” blind baseline (ranging from 11.8% to 15.1% with the largest difference being LM83 algorithm).

1. Introduction

Daylighting is a common energy-efficiency strategy that also boasts a myriad of other human benefits (Leslie 2003; Reinhart & Selkowitz 2006; Van Den Wymelenberg 2014). Successful daylighting design that saves energy and improves human satisfaction incorporates many technologies, spans several disciplines, and requires attention to detail throughout the design process and into operation.

Blinds are quite common in spaces designed for daylighting (12 out of 24 spaces in one field study per Nezamdoost and Van Den Wymelenberg (2015), since most daylighting designs will include some period of low angle sunlight, causing intermittent glare and requiring mitigation. The impact of manual and automated blinds on the performance of daylighting and energy consumption in buildings has been a subject of some inquiry (Bourgeois et al. 2006; Newsham 1994; Reinhart 2004; Van Den Wymelenberg 2012; da Silva et al. 2012; Dyke et al. 2015; Nezamdoost and Van Den Wymelenberg 2015).

According to Laouadi (2011), when closed, blinds reduce solar heat gain by 40% (with high-

performance windows) to 50% (with conventional windows) in comparison to unshaded windows. Due to daylight penetration impact, blinds can significantly alter interior lighting loads in systems with daylight sensing electric lighting controls (Heschong et al. 2005, Van Den Wymelenberg 2012).

There is a growing need to evaluate the impact of automated blind controls as an energy efficiency measure, and the baseline assumptions of the presence and/or operation of manual blinds are critical to such an evaluation. A few studies have examined the benefit of internal automated blinds in lab or field settings (Kim et al. 2009; Lee et al. 1998; Roche 2002; Dyke et al. 2015) and reported savings in peak cooling load (5-30%), cooling and ventilation energy savings (10-30%), lighting energy savings (20-45% compared to systems with photocell dimming and static blinds) and total energy savings (25%) for all systems. However, the assumptions about the baseline presence and operation of manual blinds vary in these studies.

This paper compares three leading candidates of manually-controlled window blinds plus two automated blind control algorithms using a large open plan office on the 2nd floor of a high rise building located in Boise, ID, USA. The first interior manual blind use algorithm was developed by Van Den Wymelenberg (2012) and coined “Blindswitch-2012A” by Dyke (2015), and it adjusts the blind occlusion (increased window occlusion as more blinds close) according to the sunlight penetration depth and whether exterior direct normal irradiance exceeds 120 W/m^2 . The second, Blindswitch-2012B (Van Den Wymelenberg 2012; Dyke et al. 2015), regulates occlusion based upon vertical exterior illuminance. And the third manual algorithm, proposed by the IES Daylight Metrics Committee and published as IES LM-83 (Heschong & Van Den Wymelenberg 2012; Heschong Mahone Group 2012; IESNA-Daylight

Metrics Committee 2012), adjusts blinds based upon maintaining a threshold of less than 2% of a simulated interior horizontal sensor grid exceeding 1,000 lux of direct beam sunlight with zero light bounces via digital simulation.

The automatic systems were also analysed in this paper including one interior automated blind developed by Blind Manufacturer-Automated Algorithm A (BM-AAA), and it adjusts the blinds based on vertical interior illuminance behind the window (darkness and brightness thresholds in 500 and 6000 Lux respectively) and the sunlight penetration depth in the space. The other automatic system was proposed by Blind Manufacturer-Automated Algorithm B (BM-AAB) for automated interior/exterior blinds. According to this algorithm, the blind occlusion changes based upon exterior vertical illuminance of a façade measured at the rooftop weather station and direct sun penetration depth into the space.

Further details for each algorithm are provided in the methods section. This paper compares the annual energy and daylighting performance impacts of each blind algorithm relative to one another and to multiple baselines. One baseline assumes blinds are always open and another assumes blinds always closed (best- and worst-case scenarios), both of these assume functional daylight sensing lighting controls. The paper also examines the frequency of blind movements (ROC and NBM) and average window occlusion results, spatial daylight autonomy (sDA) and annual sunlight exposures (ASE) for each blind algorithm relative to data from existing literature in order to support dialogue and eventual adoption of a consensus-based manual blind use algorithm and set of best practices for blind algorithms (both manual and automated) in daylighting and energy simulations.

2. Methods

2.1 Case Study

This paper examines a large open plan office on the second floor of a high-rise building located in downtown Boise, ID. USA (Figure 3-1 and 3-2). The case study building has an area of approximately 24,547 m² (264,218 ft²), has modest core zones and abundant open and private offices around the perimeter. The second floor (38,218 ft² area) has 112 double pane windows. The windows have a head height 3.6 m (11.7 ft) and the sill is at 0.25 m, thus the windows are 3.35 m (10.8 ft) tall. Windows wrap all facades and make up a window-to-wall ratio of 54.81% for the 2nd floor. Window U-value of 1.82 W/m²-K (0.32 Btu/hr-ft²-F), solar heat gain coefficient (SHGC) of 0.42 and visual light transmittance (VLT) of 0.72 are used throughout. Exterior walls and roof U-values are 0.25 and 0.11 W/m²-K (0.043 & 0.019 Btu/h-ft²-F), respectively. The built-up HVAC system for the second floor comprises: water-to-air heat pumps at each zone, a 90% efficient boiler to provide heat to the water loop, and a chiller (COP=5.5) to absorb the heat from the water loop. The equipment power density is 8.29 W/m² (0.77 W/ft²) and total installed lighting power density (LPD) is 11.46 W/m² (1.07 W/ft²). It was estimated that 125 occupants were on the second floor, during regular working hours (from 8 am to 6 pm, Monday through Friday). The building rotation is 35° clockwise from the North axis. Simulations were conducted with typical meteorological year 3 (TMY3) dataset for Boise, ID instead of extreme weather conditions of an actual weather year.



Figure 3-1: Case Study Building

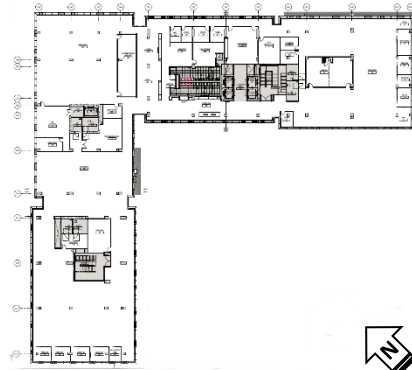


Figure 3-2: Plan View of Building

2.2 Blind Control Algorithms

Five blind control algorithms (three interior manual blind use algorithms and two interior/exterior automated blind control algorithms) were applied blinds, which were used as the primary shading devices, in order to compare their relative differences (Table 3-1) in operation patterns and resultant annual energy and daylighting impact.


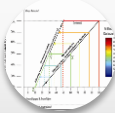
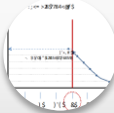
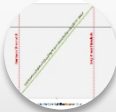

 <p>BLINDSWITCH - 2012 A</p> <ul style="list-style-type: none"> •Change the occlusion according to the penetration depth and irradiance > 120 W/m² exterior 	 <p>BLINDSWITCH - 2012 B</p> <ul style="list-style-type: none"> •Change the occlusion according to the change of vertical exterior illuminance on façade 	 <p>LM - 83</p> <ul style="list-style-type: none"> •Close the occlusion whenever more than 2% of the sensors get 1,000 lux or more of direct beam sunlight with zero bounce.
 <p>Blind Manufacturer-Automated Algorithm A (BM-AAA)</p> <p>Change the occlusion according to the change of vertical interior illuminance behind the window and sun penetration depth in the space</p>	 <p>Blind Manufacturer-Automated Algorithm B (BM-AAB)</p> <p>Change the occlusion based on exterior vertical illuminance on rooftop and eliminating direct sun penetration.</p>	

Table 3-1: Blind Control Schemes

2.2.1 Introduction of Control Algorithms

2.2.1.1 Blindswitch-A

Blindswitch-A utilizes a sunlight threshold of 120 W/m^2 of exterior irradiance measured normal to the sun and increases occlusion based on increased sunlight penetration depth (Van Den Wymelenberg 2012). As soon as sensors exceed the sunlight threshold, blind occlusion increases proportionally with sunlight penetration depth. Based upon literature review, the algorithm assumes that in reality there are always some blinds that remain “always engaged” and “always retracted”. Blind retraction is based upon a time delay (time-based hysteresis) as illustrated in Figure 3-3, serving to provide a hysteresis effect (Dyke et al. 2015).

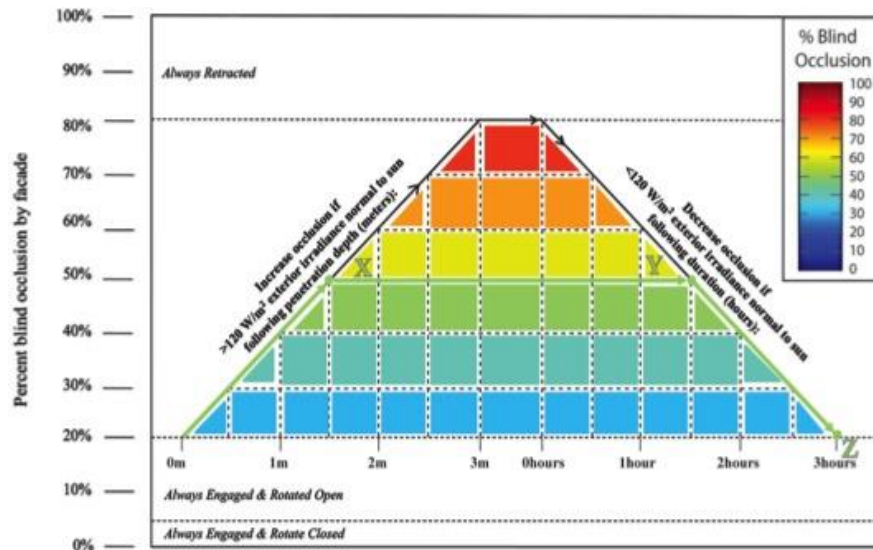


Figure 3-3: Operation Model for Blindswitch-A (Following Van Den Wymelenberg 2012 as in Dyke 2015)

2.2.1.2 Blindswitch-B

Blindswitch-B utilizes a proportional relationship between vertical exterior illuminance and blind closure as shown in Figure 3-4 (Van Den Wymelenberg 2012). Blind

closure begins when 33,000 lux of vertical exterior illuminance strikes the façade and maximum occlusion occurs at 100,000 lux. Similar to Blindswitch-A, some blinds remain retracted and some remain engaged at all times. A hysteresis effect is implemented for blind opening whereby blinds do not retract until a substantially lower exterior vertical illuminance is measured (Dyke et al. 2015).

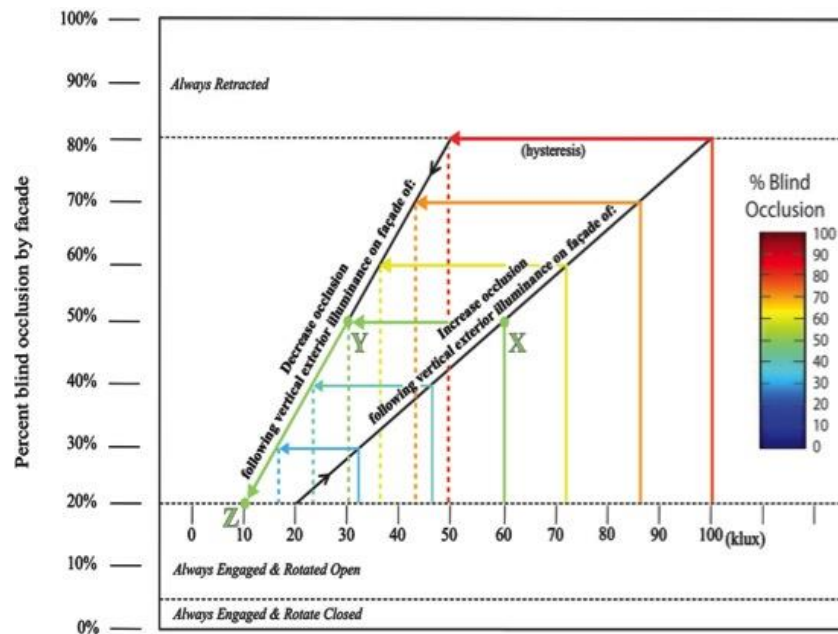


Figure 3-4: Operation Model for Blindswitch-B (Following Van Den Wymelenberg 2012 as in Dyke 2015)

2.2.1.3 IES LM-83 Metrics

The third manual blind use algorithm in this study, is based upon the simulation protocol documented in IES LM-83 (IESNA-Daylight Metrics Committee 2012). The trigger value for opening or closing interior blinds (by window group) is the percentage of floor area (2%) that exceeds a simulated 1,000 lux of sunlight, assuming zero light bounces and appropriate fixed architectural shading, cloud cover, and shading from trees and adjacent buildings. Furthermore, it is an interior horizontal illuminance measurement that includes

hourly cloud cover, glazing VLT, and the effect of angle of incidence. In LM-83, the direct sunlight calculated for determining blind closure does not consider reflected light (zero light bounces) from exterior objects or the diffuse sky component on an hourly basis. According to LM-83 documentation, blinds are closed until less than 2% of the sensors on a 0.61 m x 0.61m (2' x 2') analysis grid exceed 1000 lux. This leaves room for interpretation regarding which window blinds to close first in order to be under the 2% threshold. In this study, the worst-offender occlusion method was used, which means the worst-offending (often largest) window blind group is closed first. Also, an analysis grid of 1.22 m x 1.22 m (4' x 4') was employed in order to decrease simulation load in the expansive floor plan area of this case study. It is worth noting that the average study space size used to derive the LM-83 protocol was 120 m² (1287 ft²).

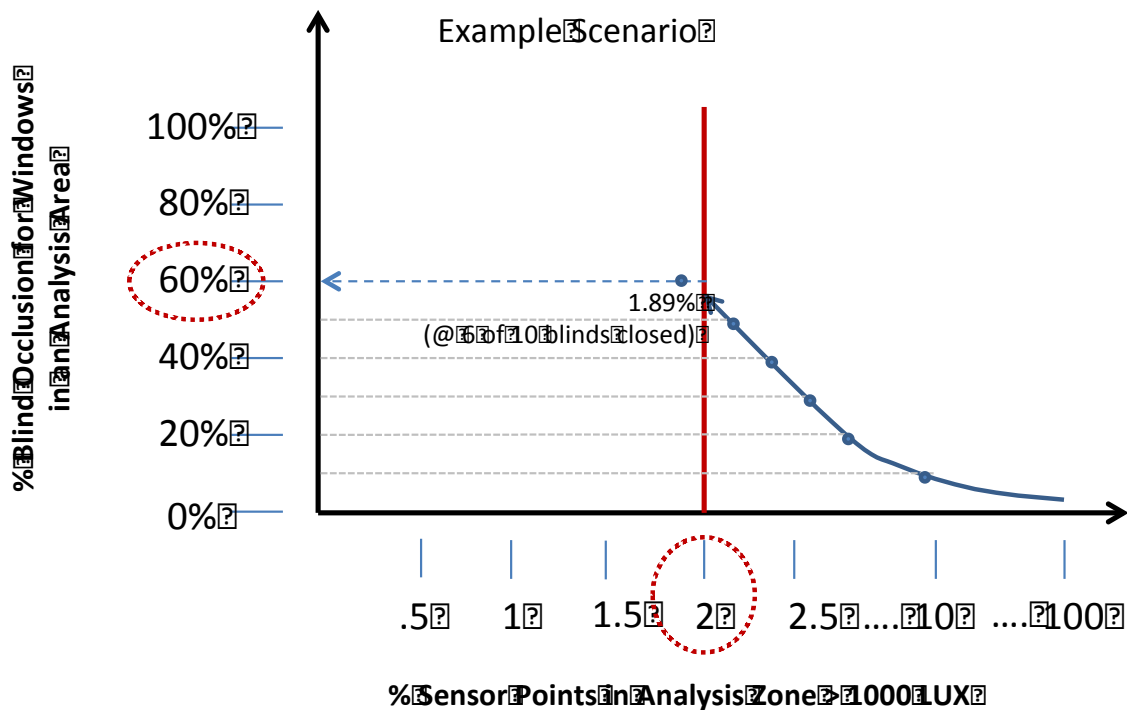


Figure 3-5: Example of LM-83 Blind Control Logic Model

2.2.1.4 Blind Manufacturer-Automated Algorithm A (BM-AAA)

Shades according to Blind Manufacturer-Automated Algorithm A (BM-AAA) are adjusted automatically in order to limit how far the direct sunlight can penetrate into a space by combining information about, sky condition, time of day and year, building location and façade orientation. The single 60° FOV(field of view) vertical illuminance sensor centered horizontally, 25% down from the window head and located behind the glass, as it shown in figure 3-6, are used to integrate information about cloud conditions and shadows from neighboring buildings. As shown in figure 3-7, if the sensor sees less than 500 Lux, the shades get fully retracted (darkness threshold) and if the sensor sees more than 6000 Lux, shades change to fully deployed position (brightness threshold). If the sensor sees a value between the darkness and brightness thresholds, the penetration depth is calculated based on the sun's position and building orientation, and if the penetration depth exceeds the maximum allowed (by default or specific setting), the shades are systematically lowered until the penetration depth is managed down to the allowable distance. In this study, the default penetration depth was used (2.5m) and instead of any possible blind positions, for sake of computational expense and limitations in the energy modeling platform to simulate partially-closed blinds, just three (0%, 50%, and 100% deployed) blind positions were allowed.

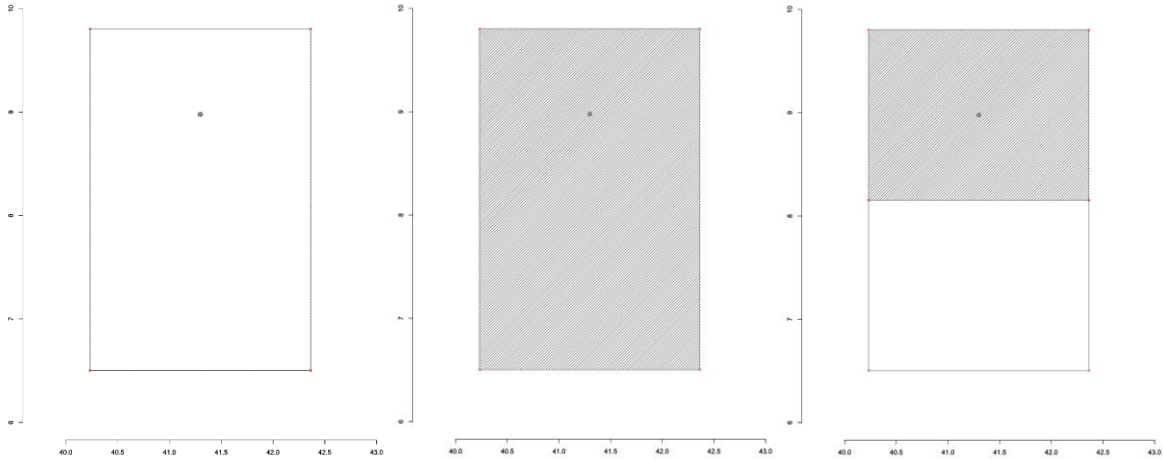


Figure 3-6: Window grouping granularity - Left to right: Fully open/ Fully closed/ Half-way closed

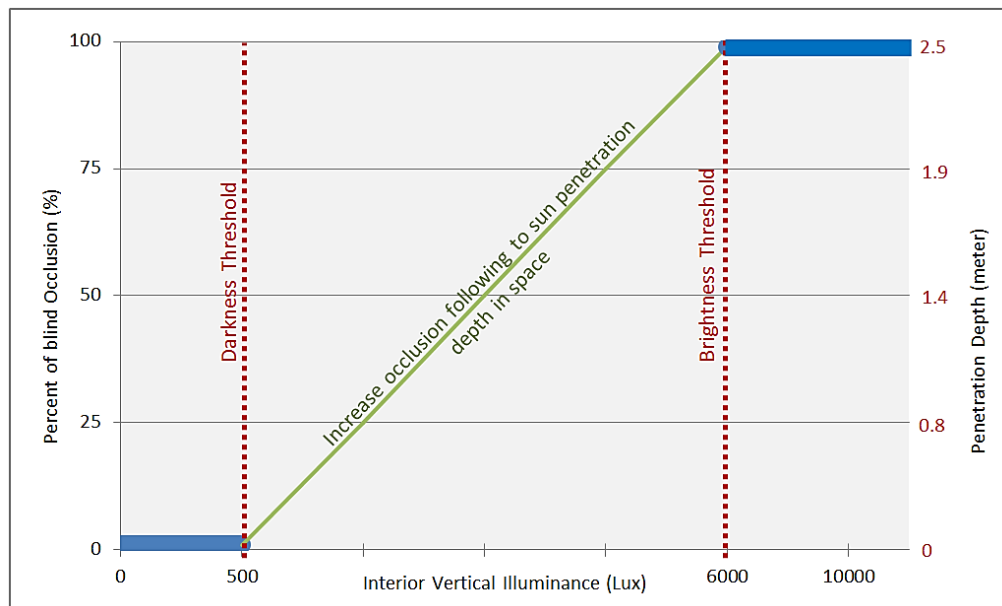


Figure 3-7: Operation Model for Blind Manufacturer-Automated Algorithm A (BM-AAA)

2.2.1.5 Blind Manufacturer-Automated Algorithm B (BM-AAB)

Blind Manufacturer-Automated Algorithm B (BM-AAB) internal/external venetian blind algorithm is operated based upon sky brightness and blinds slat tracking functions. The brightness function is used to determine whether sky condition is sunny or overcast following

an exterior vertical illuminance at the façade as measured from a rooftop weather station.

Looking at figure 3-8, if the sensor sees less than 15,000 lux of vertical exterior illuminance (default setting for cloudy) the blinds change to fully retracted. If the outdoor vertical illuminance exceeds 35,000 lux (default setting for sunny), blinds start engaging based upon a full cut-off slat tracking function. And if the exterior vertical illuminance is in between 15,000 lux and 35,000 lux, the blind position will remain in the same position as it had in the previous timestep.

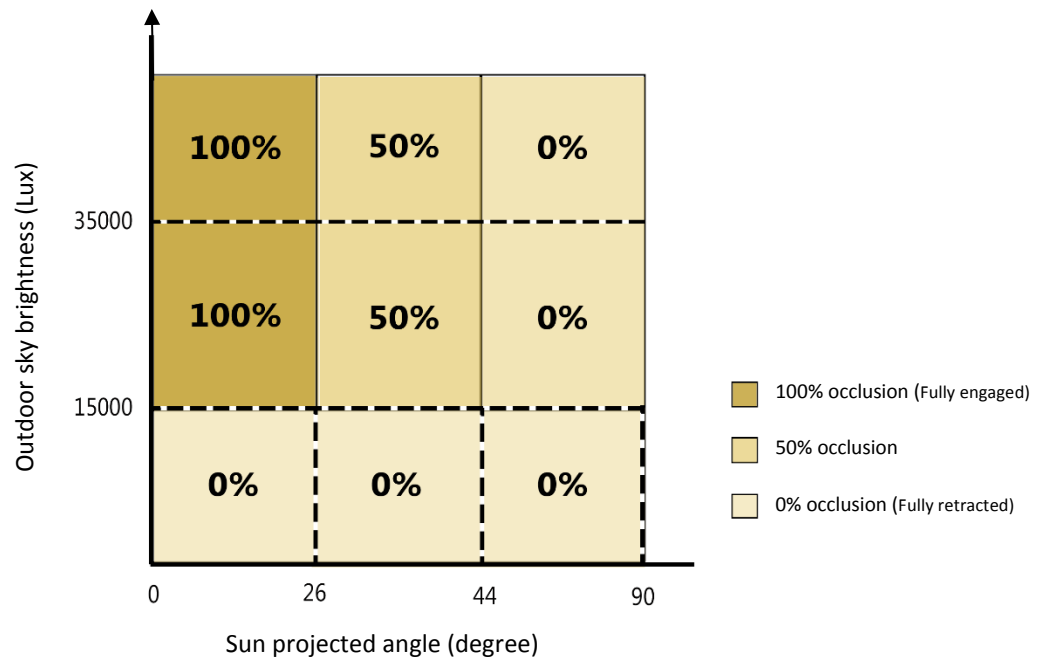


Figure 3-8: Operation Model for Blind Manufacturer-Automated Algorithm B (BM-AAB) - Simplified version

Based on manufacturer literature, the slat tracking function works to ensure that direct sunlight does not enter the room through the blind slats but positions slats so that as much diffuse daylight reaches the interior as possible. Slat tracking also allows maximum view to the outside without glare. Accordingly, at very low angles of solar incidence (solar horizontal

profile angle) the slats are rotated closed enough (75°) to prevent any dazzling solar access. As the sun rises higher, the slats rotate open further in order to provide a better view outside and bring in more daylight. In this study, for sake of computational expense and limitations and ensure consistency with window grouping granularity of Blind Manufacturer- Automated Algorithm A (fully open/fully closed/half way closed), we use three bins of sun projected angle to adjust the blind slat angle, as illustrated in figure 3-9 and table 3-2. The lower the sun projected angle, the steeper the slat angle must be to keep direct sunlight from going into the space.

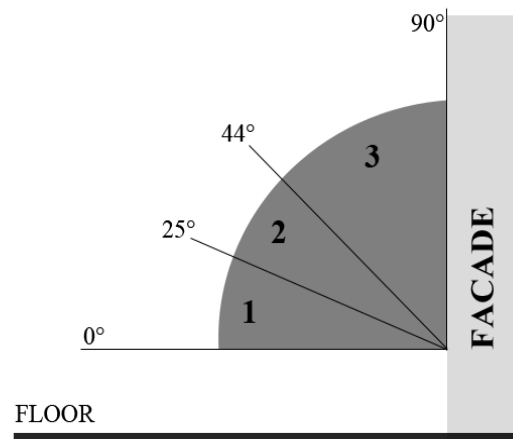


Figure 3-9: Three range of sun projected angle according to Blind Manufacturer-Automated Algorithm B (Simplified version)

Table 3-2: Range of sun projected angle to adjust slat angle in Blind Manufacturer-Automated Algorithm B (Simplified version)

Range	Projected Angle	Slat Angle
Shadow	-	-
1	$0^\circ - 25^\circ$	75°
2	$26^\circ - 43^\circ$	42°
3	$44^\circ - 90^\circ$	0°

The dawn/dusk control is another comfort function of the Blind Manufacturer-Automated Algorithm B (BM-AAB) to bring visual privacy to the occupants between dusk and dawn, through the night. This function happens only one time per day, engaging when the outdoor vertical illuminance decreases to below 80 Lux at dusk and retracting when the outdoor illuminance reaches 50 Lux after dawn.

2.3 Simulation Parameters

2.3.1 Daylight modelling development

For annual climate-based daylight simulation, detailed digital interior models and relevant massing of surrounding buildings and site context were generated in SketchUp version 2014. The simulation protocol outlined in LM-83 (IESNA-Daylight Metrics Committee 2012) was strictly adhered to unless noted otherwise. When the model was completed and verified for accuracy against floor plans; it was exported to the RADIANCE daylight simulation engine. *Rcontrib* ambient calculations were used in RADIANCE to compute light source contributions. Materials and shades were assigned to digital models based on the information from construction specifications using CIBSE surfaces and reflectance charts and bi-directional scattering and distribution functions (BSDF). Moreover, below in table 3-3, a list of the RADIANCE simulations parameters for all study spaces is documented. An illuminance analysis grid of 4'x4' was used (2176 analysis points) for generating illuminance point data in this large-sized case study to decrease simulation load.

Table 3-3 RADIANCE Simulation Parameters

Ambient bounces	Ambient division	Ambient sampling	Ambient accuracy	Ambient resolution	Direct threshold
6	4096	1024	0.1	256	0

According to IES LM-83 2012 documentation (section 2.2.6 Blinds/Shades Operation): "... For the purpose of deriving the blinds operation schedules, analysis areas shall be considered by façade orientation, and never exceed 10,000 sf. The analysis grids must also extend across the entire space." Therefore, the authors decided to break down the entire floor plate into four spatial daylight zones with areas less than 10,000 sf, as shown on figure 3-10, and analyze blinds operation based on zoning of spaces and window groups in the annual simulations.

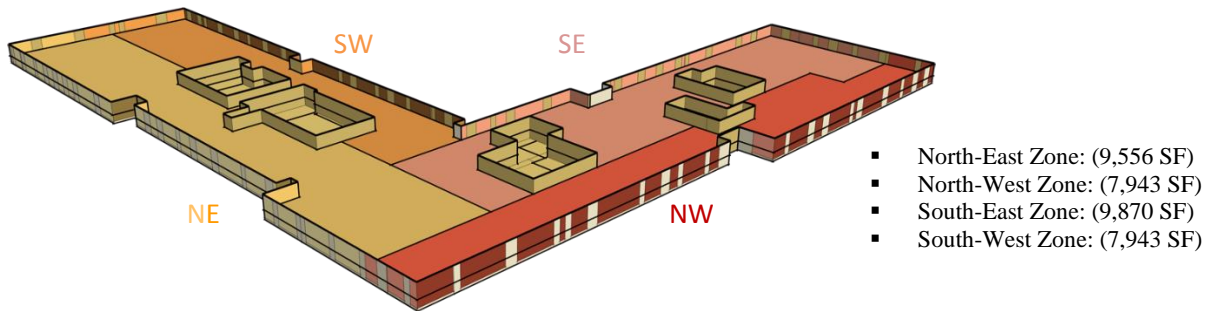


Figure 3-10: RADIANCE model structure – Daylight zoning

2.3.2 Simulating Dynamic Operated Blinds

2.3.2.1 Blindswitch-A

All facades were broken down into 10 window groups, each with individually controllable blinds. For the Blindswitch 2012-A algorithm, windows were assigned a number from 1-10 in random fashion, and each number had one of four blind operation types assigned. Windows #1-#2 were always engaged, windows #3-8 were operated by the algorithm, and windows #9-10 are always retracted. For those facades having fewer or more than 10 logical window groups, an approximate scaling with some randomization of the ten

possible window group definitions were applied. If there was only one window in the space, it was considered as operable window group number five for Blindswitch-A. If there were two windows in a space, operable window groups number four and six were randomly applied to each window blind. For three windows in a space, window group numbers three, five and seven were randomly applied to the window blinds. If between four and nine logical window groups existed, the scenario of three windows was repeated plus one additional window group was randomly assigned for each additional logical window group in the space (Nezamdoost and Van Den Wymelenberg, 2015).

The Energy Management System (EMS) in EnergyPlus (Version 8.3.0) was used to create blind occlusion schedules. It utilizes two inputs for blind control: (1) exterior irradiance based upon direct solar data from the weather file, (2) sunlight penetration depth based upon Solar Horizontal Profile Angle output. A timestep of half an hour was used for Blindswitch-A, with the half hour time step used to accommodate the hysteresis of the algorithm (Figure 3-3).

In order to calculate indoor horizontal illuminance for daylight sensing lighting control and creating the lighting/dimming fractional schedule, an overlaying procedure between EnergyPlus thermal zones and RADIANCE daylight zones was needed. As it is shown in figure 3-11, the authors started with (1) EnergyPlus model including all the thermal zones (41 on second floor), (2) a script-based analysis grid was generated based on four daylight zones in RADIANCE, (3) EnergyPlus thermal zones overlaid onto the RADIANCE analysis grid in order to isolate the illuminance grid points that fall inside the EnergyPlus thermal zone. These can be averaged, or a single point specified to generate the fractional lighting schedule, and

(4) reconciling zone overlays in R-studio. This is a critical step to ensure accurate energy simulation of the interactive effects of daylight sensing electric lighting control.

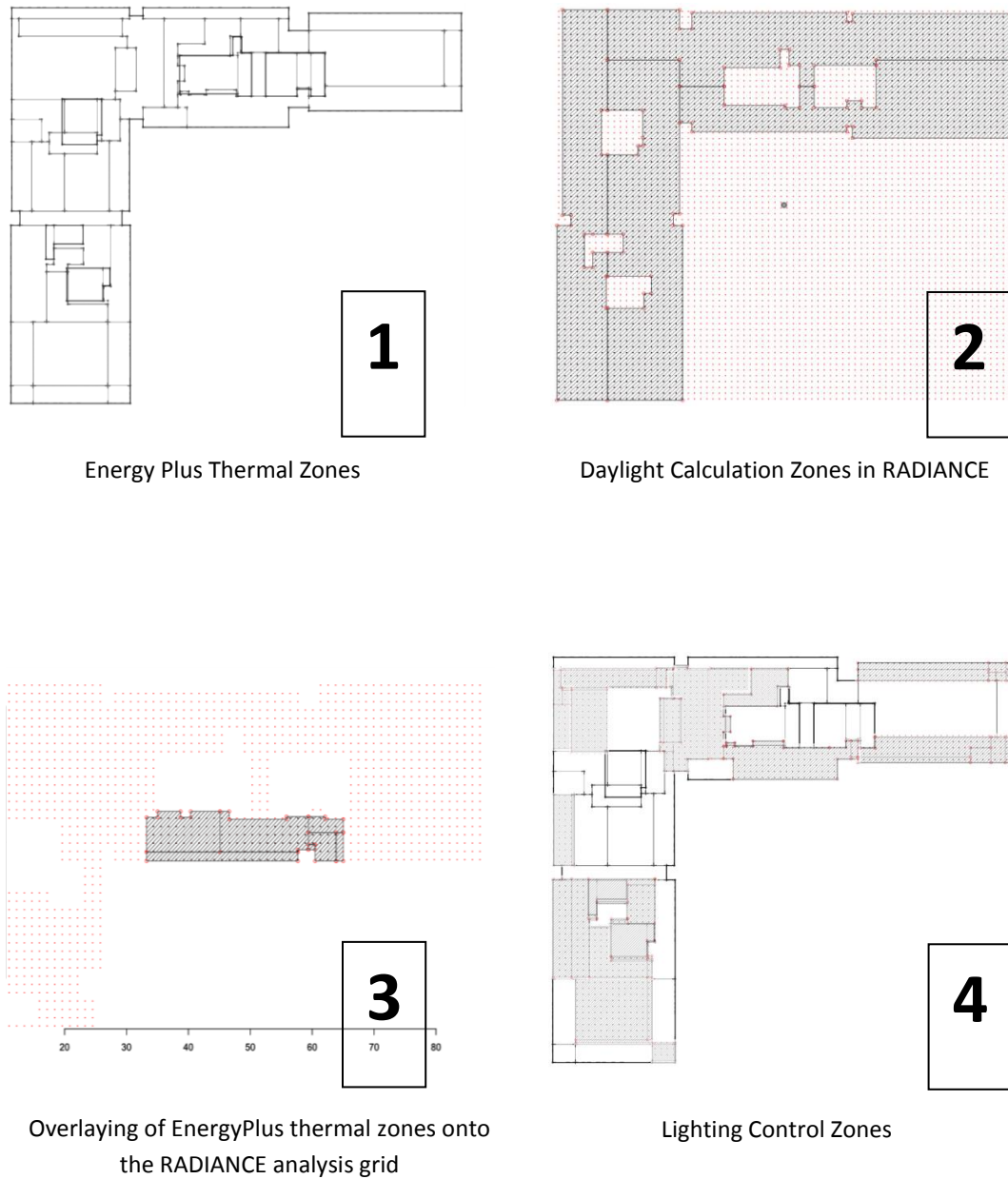


Figure 3-11: Calculation of indoor horizontal illuminance for daylight sensing lighting control and creating lighting/dimming fractional schedule

As mentioned, in order to calculate sun penetration depth in EnergyPlus, Solar Horizontal Profile Angle was captured from the EMS module in EnergyPlus. The calculation of Horizontal Profile Angle is based upon the angle between each window outward normal and the projection of the sun's ray, but it doesn't take building self-shading into account automatically. In this study, the L-shape building produces substantial building self-shaded areas on the south-west facade in the morning and the south-east facade in the afternoon. Therefore, the authors decided to define exterior vertical sensors outside the windows, and whenever the vertical illuminance on an area within the facade dropped below 10,000 Lux, it overrides the horizontal profile angle calculation and changes the blinds position to retracted. This ensures that the simulated blinds operate according to the algorithm and account for building self-shading.

2.3.2.2 Blindswitch-B

Similar to Blindswitch-A, 10 window groups were used per façade but was run with one-hour timesteps; however, unlike Blindswitch-A, Blindswitch-B utilizes vertical exterior illuminance data as the main input for the algorithm. Moreover, similar to Blindswitch-A, for those facades having fewer or more than 10 logical window groups, an approximate scaling with some randomization of the ten possible window group definitions were applied. Blindswitch-B also utilizes the EnergyPlus EMS module, but in combination with vertical exterior illuminance data obtained from RADIANCE (Version 4.2.0). As shown in figure 3-12, in order to calculate exterior vertical illuminance, an analysis point was defined just outside the window on each façade, at the height of the work plane (0.76 m or 2.5 ft). Indoor horizontal illuminance for daylight sensing lighting control was calculated using the same analysis grid points described for Blindswitch-A.

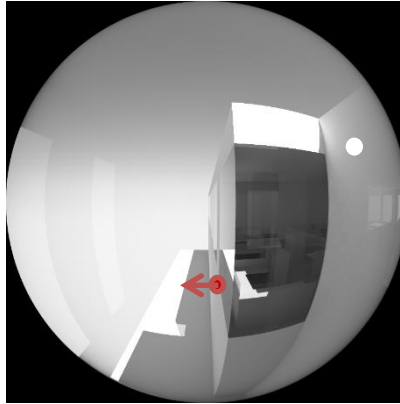


Figure 3-12: Exterior Vertical Illuminance

2.3.2.3 IES LM-83 Metrics

To maintain consistency for sake of results comparison, LM-83 as well as Blindswitch-A and -B all used the same window-grouping method for each façade. The blind trigger in LM-83 is designed to maintain less than 2% of the sensors in a specified floor area in excess of 1000 lux (zero bounces). Therefore, the trigger value for all operable blinds (#1-10) is potentially the same, until less than 2% of the sensor grid exceeds 1,000 lux. To clarify, Figure 3-13 illustrates an example of the LM-83 control decisions for 10 individual windows within one space, on April 10th at noon. It also illustrates that window blinds are closed from worst to least offender, until less than 2% of sensors exceed 1000 lux. Indoor horizontal illuminance for daylight sensing lighting control was calculated the same way as described for Blindswitch-A and –B above. It is important to note that, by definition, the LM-83 2% trigger potentially operates all 10 window blind groups, not just the six blinds as is the case with Blindswitch-A and Blindswitch-B.

```

4      10      12      | 3.21% of sensors are above 1000 lux, evaluating window groups.
      | >> zn_sw_14_s is contributing 0.23% of the total 3.21% in the space, closing.
      | >> zn_sw_16_s is contributing 0.18% of the total 3.21% in the space, closing.
      | >> zn_se_05_e is contributing 0.18% of the total 3.21% in the space, closing.
      | >> zn_sw_17a_s is contributing 0.14% of the total 3.21% in the space, closing.
      | >> zn_sw_12b_s is contributing 0.14% of the total 3.21% in the space, closing.
      | >> zn_sw_05_e is contributing 0.14% of the total 3.21% in the space, closing.
      | >> zn_sw_03b_e is contributing 0.14% of the total 3.21% in the space, closing.
      | >> zn_se_13_e is contributing 0.14% of the total 3.21% in the space, closing.
      | >> Less than 2% achieved by closing: zn_sw_14_s zn_sw_16_s zn_se_05_e
zn_sw_17a_s zn_sw_12b_s zn_sw_05_e zn_sw_03b_e zn_se_13_e (-1.29%)

```

Figure 3-13: Example of the LM-83 control decisions for ten windows

2.3.2.4 Blind Manufacturer-Automated Algorithm A (BM-AAA)

Blind Manufacturer-Automated Algorithm A (BM-AAA), as well as the three manual blind use algorithms, used the 10 window grouping method for each façade, and potentially operates all 10 window blind groups. It also utilizes EnergyPlus to calculate horizontal profile angle on each façade. Moreover, a single vertical illuminance sensor was employed behind the glass with 60° field of view (figure 3-14) for each window in RADIANCE. Blind schedules were generated according to the combination of exterior illuminance data obtained from RADIANCE, plus horizontal profile angle from EnergyPlus. The grid of analysis points (1.22 m x 1.22 m (4' x 4')) is defined at the work plane level; the core zones similar to LM-83 algorithm were excluded. Indoor horizontal illuminance for daylight sensing lighting control was calculated the same way as in Blindswitch-A.

Since there is a limit in EnergyPlus for simulating partially-closed shades (i.e. just open/closed positions are allowed) and it was a time-consuming process to split all of the 112 windows on the second floor by other means, the authors decided to change the quantity of timesteps from 1 (hourly) to 2 (30 minutes) in energy simulation. Accordingly, in energy analysis, those blinds with half-way closed position were simulated 30 minutes open and 30 minutes closed and results integrated.

Since there is a limit in EnergyPlus for simulating partially-closed shades (i.e. just open/closed positions are allowed) and it was a time-consuming process to split all of the 112 windows on second floor, the authors decided to change the quantity of timesteps from 1 (hourly) to 2 (30 minutes) in energy simulation. Accordingly, in energy analysis, those blinds with half-way closed position were simulated 30 minutes open and 30 minutes closed.

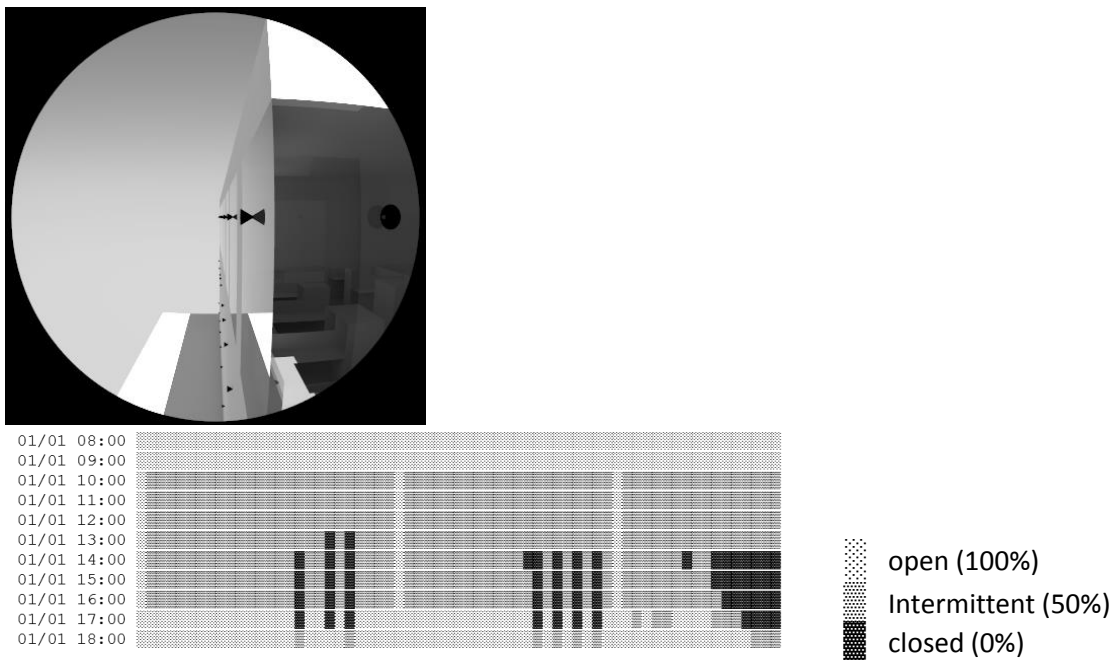


Figure 3-14: Top: 60° field of view vertical illuminance sensors – Bottom: Example of Automated Algorithm A (BM-AAA) blind simulation

2.3.2.5 Blind Manufacturer-Automated Algorithm B (BM-AAB)

Similar to the other four blind control algorithms, Automated Algorithm B (BM-AAB) employed window-grouping method for all facades. According to the factory settings, four exterior vertical illuminance sensors were defined (each for one orientation) on the rooftop in RADIANCE to support the data needed for sky brightness function. The quantity of sensors (four) caused low sensitivity in blind operation. It means in a bright sunny day, all the blinds on a facade engage together and all remain close until the outdoor vertical illuminance decrease and then all the blinds retract together. Furthermore, this actual real building control algorithm uses a rooftop weather station. That means it will miss building self-shading in reality.

EnergyPlus EMS was also employed to calculate blind slat tilt angle based upon sun position (altitude and azimuth) and horizontal profile angle. Given these two datasets, blind schedules were generated. Lighting/dimming schedules and indoor horizontal illuminance for daylight sensing lighting control was calculated the same in Blindswitch-A.

2.4 Simulation workflow

Each algorithm, Blindswitch-A, -B, LM-83, Automated Algorithm A (BM-AAA) and Automated Algorithm B (BM-AAB) require unique simulation pathways to conduct accurate and effective annual daylight and whole building energy simulation, and daylight sensing electric lighting control. In all cases integrated simulation of EnergyPlus and RADIANCE is needed. The procedure for integration is displayed in figure 3-15 for Blindswitch-A and Automated Algorithm B (BM-AAB), in Figure 3-16 for Blindswitch-B, and in Figure 3-17 for LM-83 and Automated Algorithm A (BM-AAA).

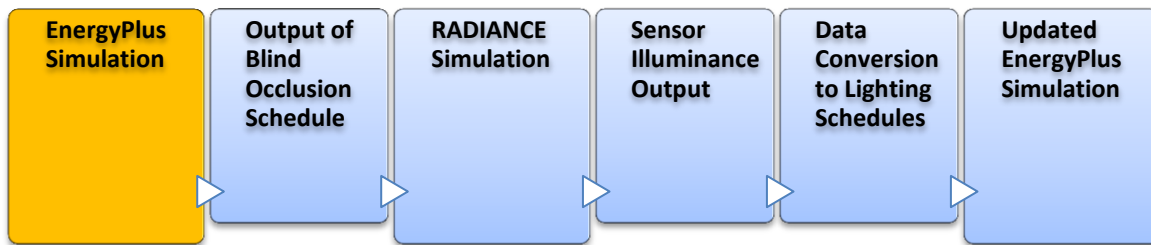


Figure 3-15: EnergyPlus/ RADIANCE integration workflow for Blindswitch-A and Automated Algorithm B

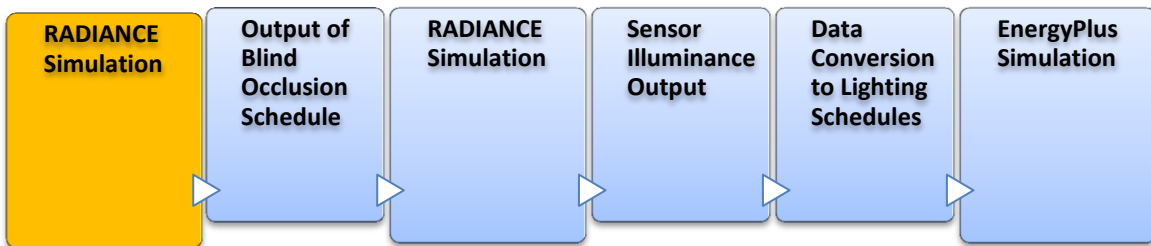


Figure 3-16: EnergyPlus/ RADIANCE integration workflow for Blindswitch-B

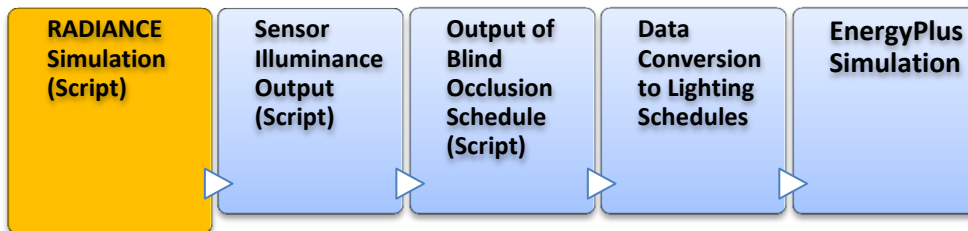


Figure 3-17: EnergyPlus/ RADIANCE integration workflow for LM-83 and Automated AlgorithmA

3. Results

3.1 Blind Movements

Rate of change (ROC) and number of blind movements (NBM) are used to examine the behavior of blind use algorithms. ROC is based only on blind movement per façade, that is, a particular blind either engages or retracts at least one time (can be measured over any time period, but we present daily results). However, ROC does not take into account the

number of times a blind position changes in a day. Therefore, NBM is needed, and it represents the ratio of the total number of blind movements per day to the total number of blinds that moved (at least once) per day per façade.

Table 3-4 and figure 3-18 provide the comparison of annual average of daily ROC values for five proposed blind algorithms (Blindswitch-A: Red, Blindswitch-B: Blue, IES LM-83: Green, Blind Manufacturer-Automated Algorithm A: Purple, and Blind Manufacturer-Automated Algorithm B: Orange) in all different facades. As expected, these plots show that automated blind algorithms are the most active algorithms of all five. Blind Manufacturer-Automated Algorithm B (BM-AAB) results in the highest annual average of daily ROC for all facades, reaching 100%, due to the dawn/dusk privacy functionality during night-time hours (engaging all blinds at dusk and opening them at dawn). Moreover, it is interesting to note that between the three manual blind use algorithms, Blindswitch-A has the highest annual average of daily ROC, thus can be interpreted as the most active manual blind use algorithm. As shown in Figure 3-18, Blindswitch-B is less variable with regard to consecutive daily ROC values than the other algorithms. It should be noted that for LM-83, Automated Algorithm A and Automated Algorithm B, all of the window groups' blinds are operable, making 100% ROC possible, whereas the inherent definition of Blindswitch-A and -B, having some blinds down and some up at all times, it is not possible to reach 100% ROC.

Blind Manufacturer-Automated Algorithm A (BM-AAA) and LM-83 show high rate of change during summer-time on the North-east and North-west facades while on South-east and South-west facades the highest blind activity is recorded in winter. This is likely due to low angle sun position and greater depth of sun penetration in winter versus summer and East/West orientations versus South.

On the North-east façade, Blindswitch-A shows a high ROC value due to deep sun penetration in the mornings. Blind Manufacturer-Automated Algorithm A (BM-AAA) uses the same foundational logic (sun penetration depth) but the ROC value is less than half of Blindswitch-A (21.84% versus 55.97%). This is likely due to interior vertical illuminance function in the Blind Manufacturer-Automated Algorithm A as compared to Blindswitch-A. When examining the differences between Blindswitch-A and Automated Algorithm A rate of change results, it appears that most of the blind movements (closures) occur in the mornings with the Blindswitch-A, whereas, and the Automated Algorithm A does not operate because the sky brightness stimulus is not high enough to trigger closure.

Table 3-4: Annual average daily blind ROC by façade for each blind control algorithm

ROC	BSA	BSB	LM83	BM-AAA	BM-AAB
NE	55.97	19.33	18.63	21.84	100.00
SE	73.62	49.18	61.44	86.65	100.00
NW	62.23	30.39	51.11	54.38	100.00
SW	71.03	53.87	51.86	85.79	100.00
Average	65.55	37.95	44.92	61.36	100.00

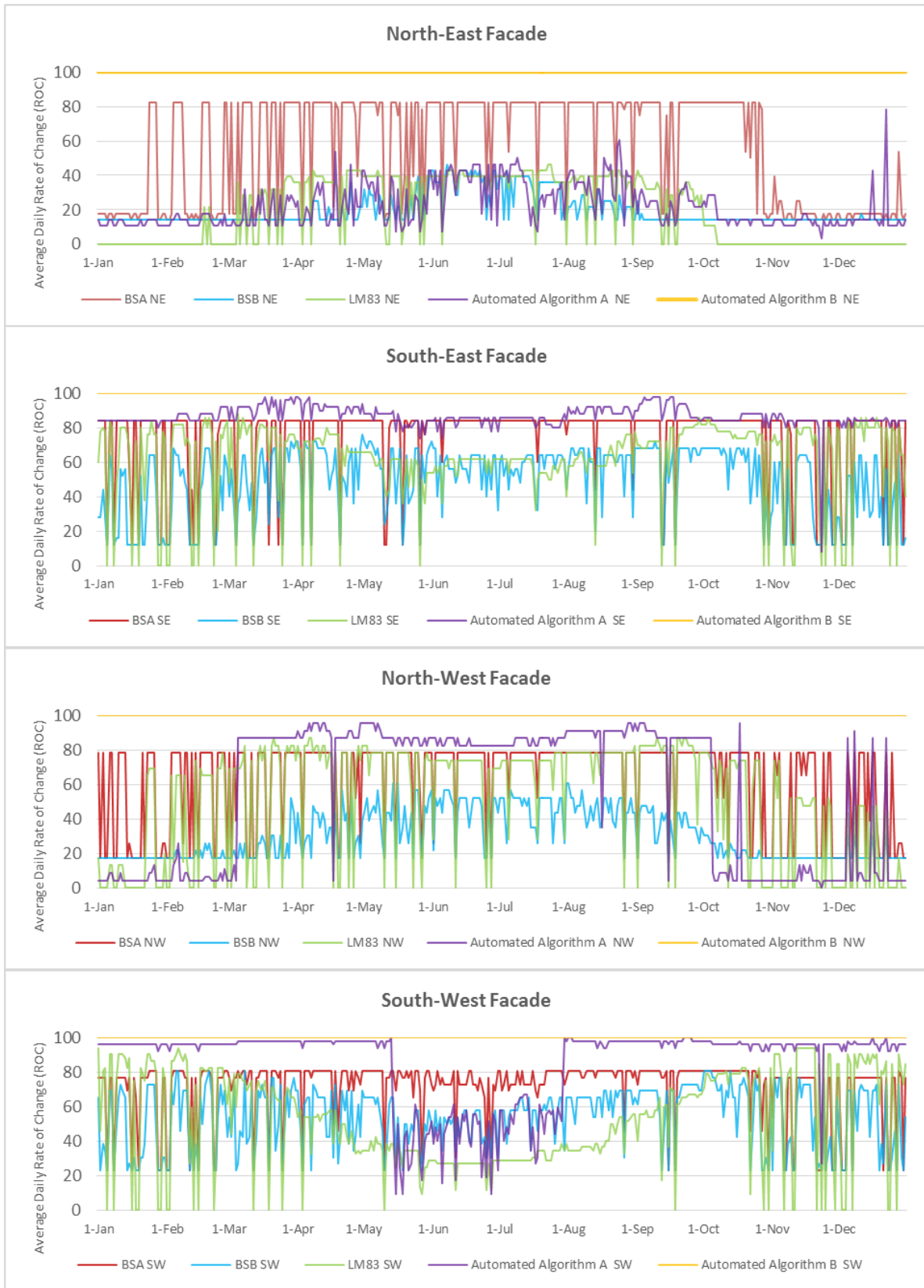


Figure 3-18: Annual daily ROC by façade for each blind control algorithm



Figure 3-19: Annual daily NBM by façade for each blind control algorithm

Figure 3-19 and table 3-5 display the NBM values for Blindswitch-A, -B, LM-83, Automated Algorithm A (BM-AAA) and Automated Algorithm B (BM-AAB). As it was expected, automated blind control algorithms (Automated Algorithm A and Automated Algorithm B) show more frequent movement than manual blind algorithms. Although the values for the three manual blind use algorithms are more or less similar, LM-83 shows the highest NBM during the course of the year, except on North-east façade where Blindswitch-A shows the highest values. Generally the figures for Blindswitch-A & -B change between 0 and 2, which is a logical daily blind operation pattern, typically engaging in the morning and retracting in the afternoon/evening. Some exceptions can be seen in Blindswitch-B with average NBM of 3 or 4 on some days, and also for Blindswitch-A on the North-East facade. The NBM values for LM-83 are not limited between 0 and 2 and there are more irregular numbers as compared to Blindswitch-A or B, with considerably higher blind use activity on South facades.

Table 3-5: Annual average daily blind NBM by façade for each blind control algorithm

NBM	BSA	BSB	LM83	BM-AAA	BM-AAB
NE	1.83	0.59	1.04	2.76	2.00
SE	1.74	1.70	2.05	3.13	3.12
NW	1.55	1.15	1.50	2.72	2.43
SW	1.82	1.74	2.05	2.87	3.18
Average	1.74	1.28	1.65	2.87	2.67

3.2 Average Percent Occlusion

Figure 3-20 illustrates the annual average occlusion values for each facade for each of the five blind algorithms in both whole day (24 hours) and “occupied hours” only (8AM-6PM). As expected, the lowest percentage average occlusion for Blindswitch-A, -B, LM-83, Automated Algorithm A (BM-AAA) and Automated Algorithm B (BM-AAB) was recorded for the North façades (NE and NW). In both timespans, the highest occlusion for all five algorithms belongs to the South-West facade. During occupied hours, LM-83 shows the lowest average blind occlusion for every façade, while the highest average blind closure is recorded for Blindswitch-A. It is worth noting that with the LM-83 manual algorithm and the two automated control algorithms, all 10 window groups are treated as having operable blinds, thus increasing the “ceiling” and decreasing the “floor” of possible average blind occlusion values.

In the 24-hour timespan, Blind Manufacturer-Automated Algorithm B (BM-AAB) shows considerably higher average blind occlusion than other algorithms (almost twice or more) on all facades, which is due to dawn/dusk function during night-time hours. As expected, automated blind control algorithms, show lower average blind occlusion compared to manual blind use algorithms (except LM-83). Although, occlusion percentages in Automated Algorithm A (BM-AAA) and Automated Algorithm B (BM-AAB) are increased on South-facing facades, they are still less than Blindswitch-A and Blindswitch-B.

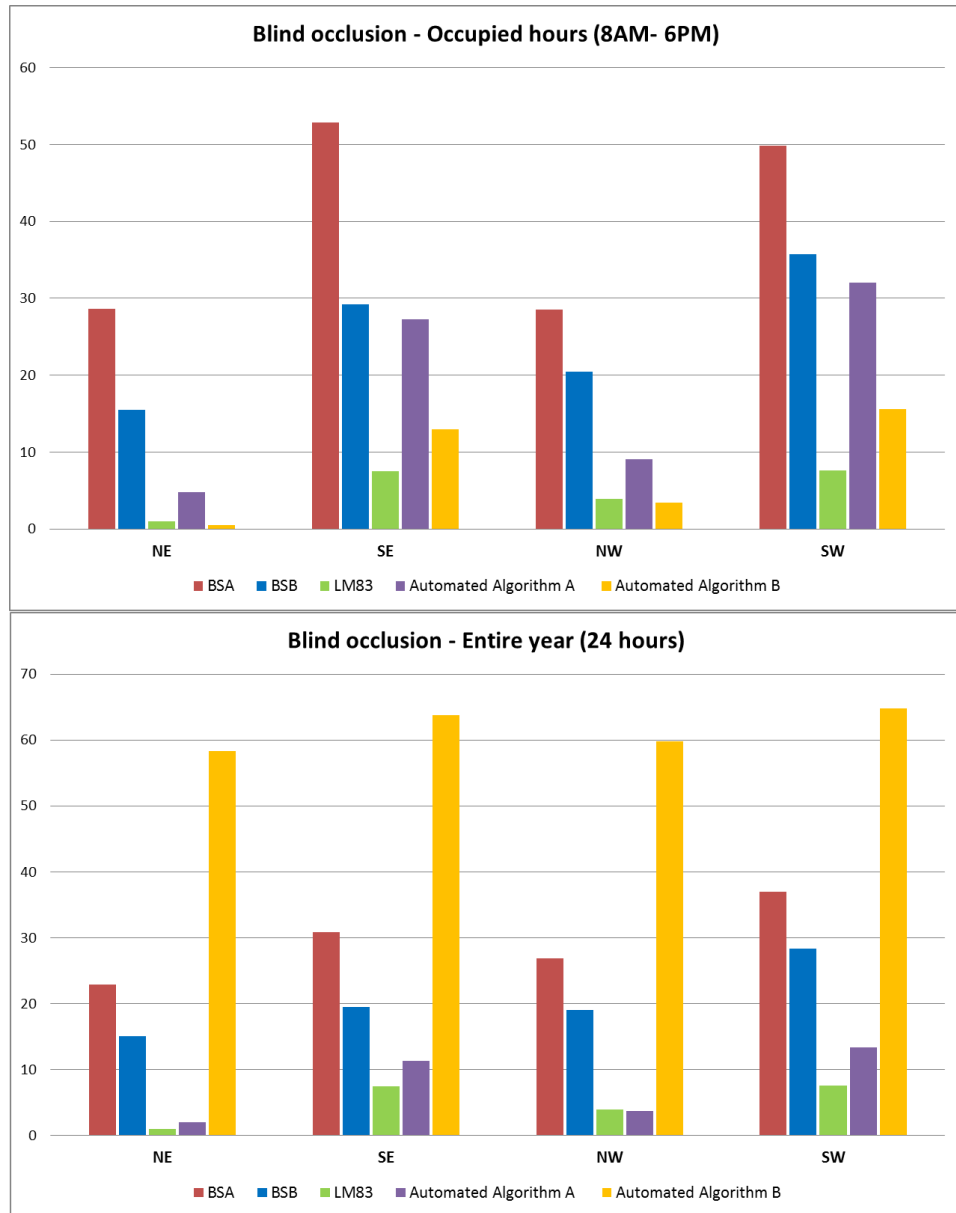


Figure 3-20: Annual Average Percent Occlusion by façade for each blind control algorithm, examining 24 hour data and occupied hours only.

3.3 Daylight Analysis

3.3.1 Daylight Sufficiency (sDA)

In order to provide meaningful guidance for designers regarding the sufficiency of daylight illuminance available in a design, a metric called spatial Daylight Autonomy (sDA)

was developed by the IES Daylight Metrics Committee based conceptually upon Daylight Autonomy (Reinhart & Walkenhorst 2001), and a second titled Annual Sunlight Exposure (ASE) was developed to suggest possible risk of excessive sunlight (IESNA, 2012). Both are documented in the IES LM-83 publication with simulation parameters carefully documented, including the LM-83 blind control algorithm, and both are summed to a single number for a space. This metric was defined to make possible the evaluation of one space to another in regard to daylight performance or to compare alternate design strategies for a single space. The sDA reports a percentage of floor area that exceeds a specified illuminance level (e.g. 300 lux) for a specified amount of annual occupied hours (e.g. 50% of the hours from 8am-6pm annually). The plots below show noticeable differences in the size and shape of the “daylit areas” (meaning, the analysis area above 300Lux during 50% of occupied hours) relative to simulated annual daylight availability based on interior manual and automated blind algorithms. Additionally, two baseline cases were run, blinds always open and blinds always closed (best- and worst-case scenarios). The substantial difference between sDA percentages of “always closed” and “always open” (0.97% versus 86.31%) confirms that blind use has potentially significant impacts on daylight availability in spaces.

The sDA for blinds operated according to Blind Manufacturer-Automated Algorithm B (BM-AAB) and IES LM-83 manual blind algorithm show the highest values, 84.05% and 82.54% respectively. As it was expected, given the lower blind occlusion percentages, Blindswitch-A and Blind Manufacturer-Automated Algorithm A (BM-AAA) show the lowest sDA annual illuminance values, 70.86% and 73.16% respectively.

Table 3-6: Average annual spatial Daylight Autonomy for each blind control algorithm

	Always closed	Always Open	LM-83	Blindswitch -A	Blindswitch -B	Blind Manufacturer -Automated Algorithm B (BM-AAB)	Blind Manufacturer -Automated Algorithm B (BM-AAB)
sDA 300lux/50%	0.97%	86.31%	82.54%	70.86%	79.37%	73.16%	84.05%

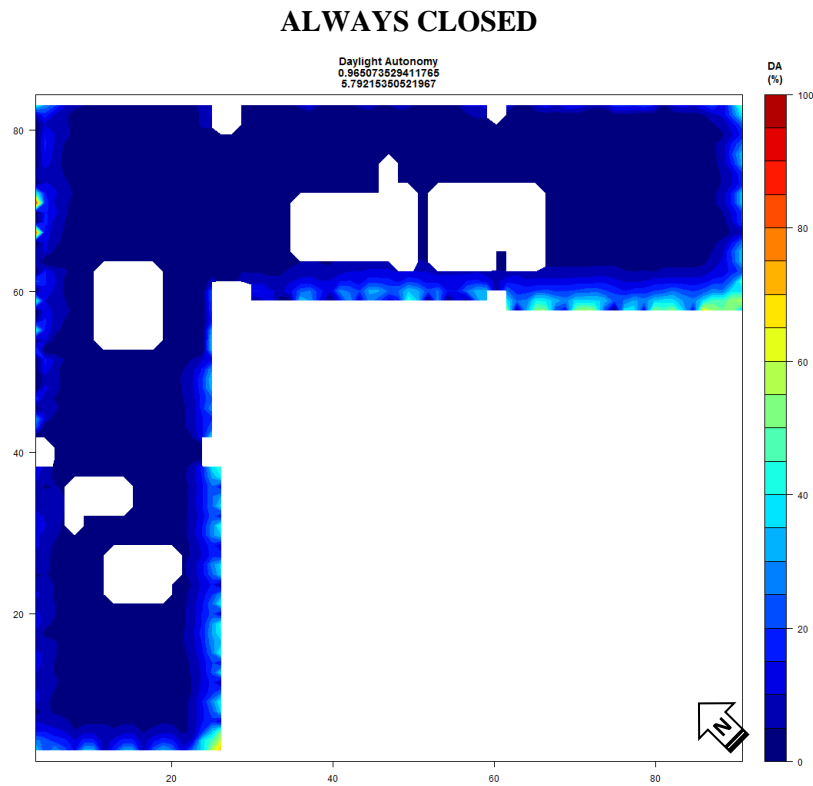


Figure 3-21: spatial Daylight Autonomy plot for each blind control algorithm

ALWAYS OPEN

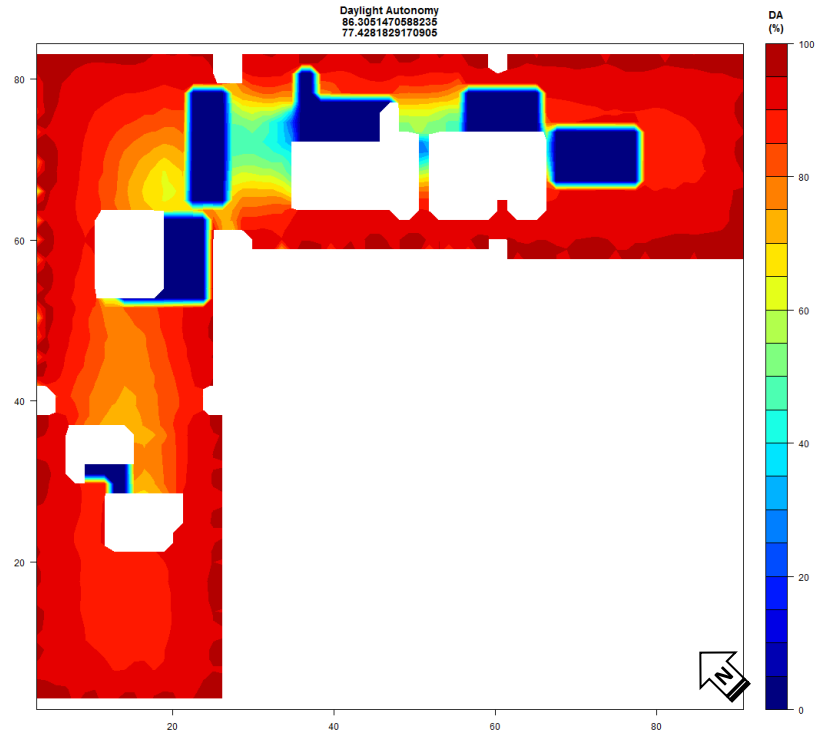


Figure 3-21: spatial Daylight Autonomy plot for each blind control algorithm

IES-LM-83

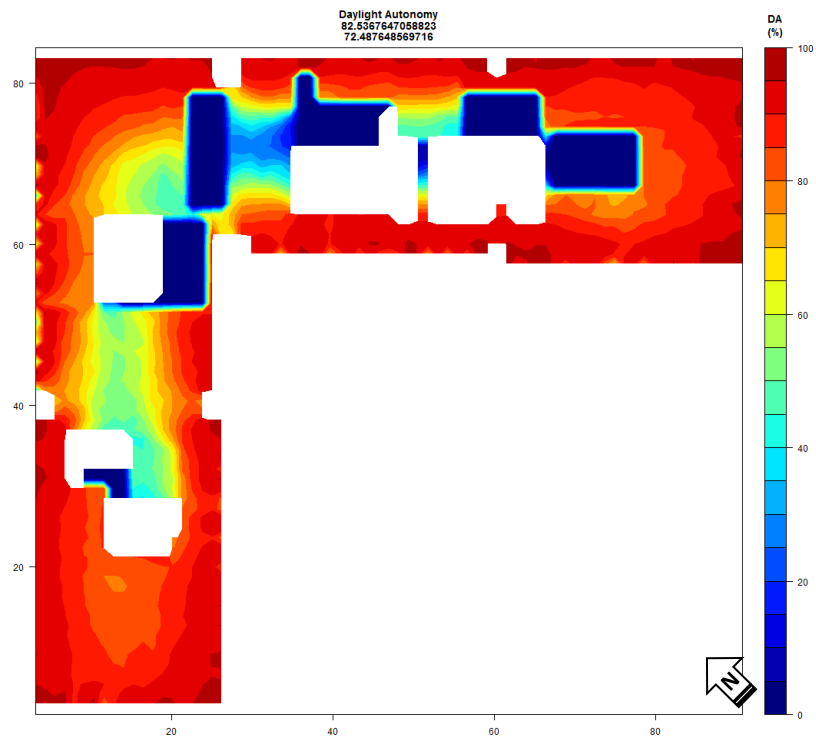


Figure 3-21: spatial Daylight Autonomy plot for each blind control algorithm

BLINDSWITCH-A

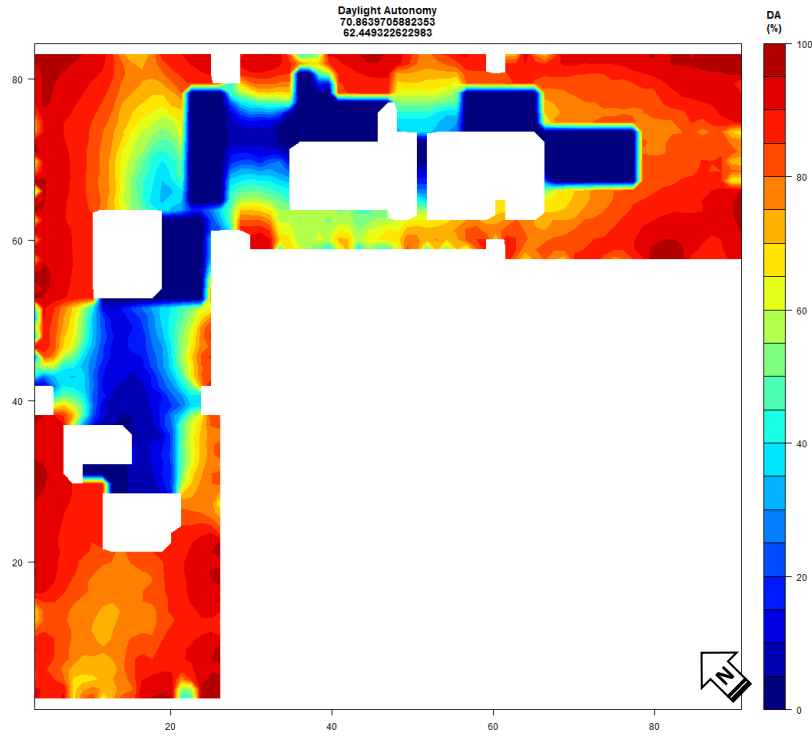


Figure 3-21: spatial Daylight Autonomy plot for each blind control algorithm

BLINDSWITCH-B

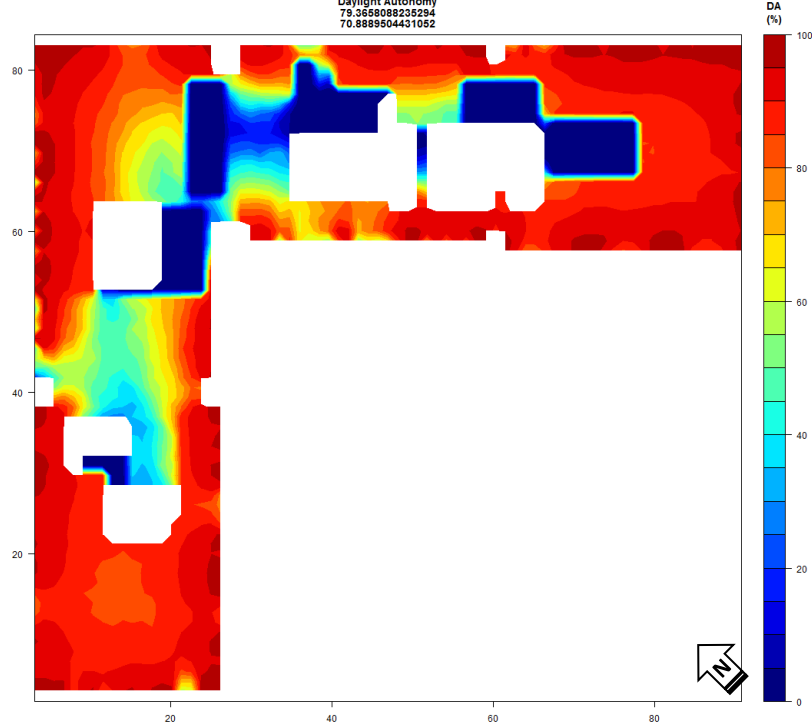


Figure 3-21: spatial Daylight Autonomy plot for each blind control algorithm

BLIND MANUFACTURER-AUTOMATED ALGORITHM A (BM-AAA)

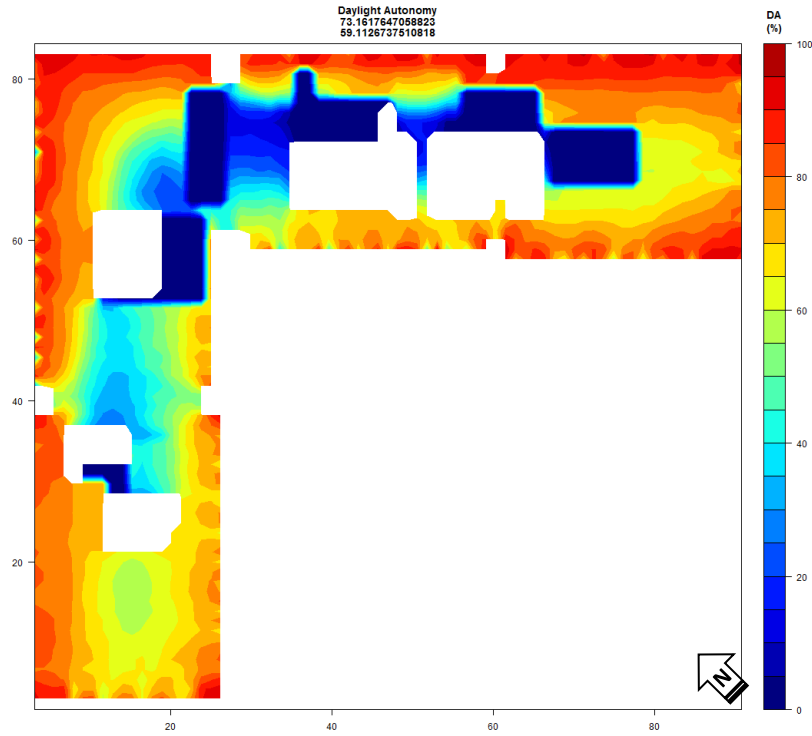


Figure 3-21: spatial Daylight Autonomy plot for each blind control algorithm

BLIND MANUFACTURER-AUTOMATED ALGORITHM B (BM-AAB)

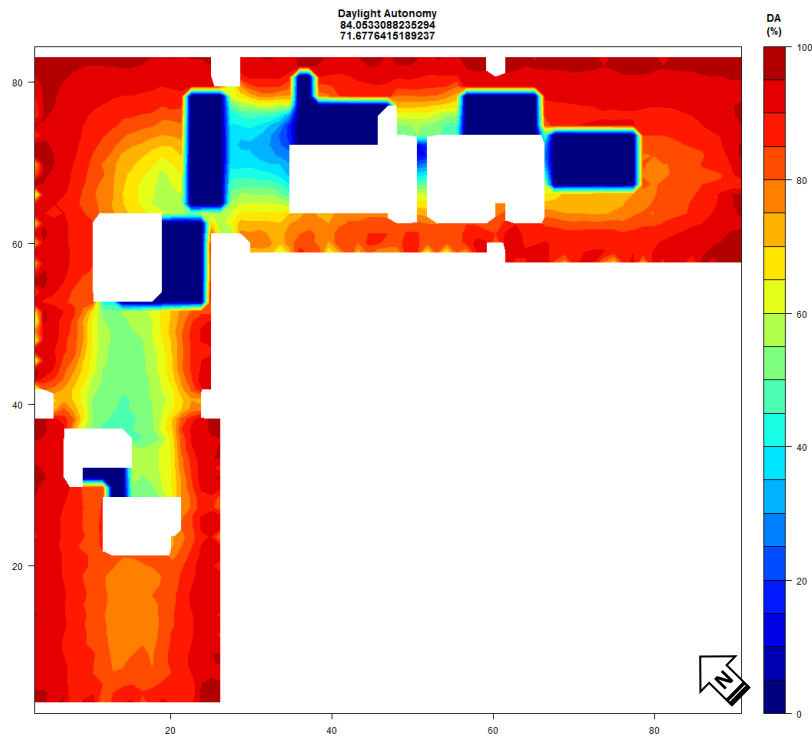
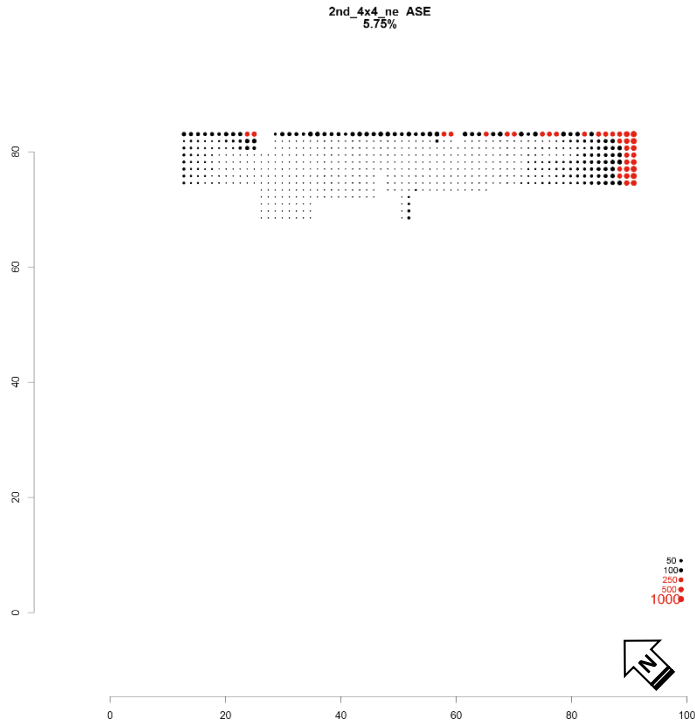


Figure 3-21: spatial Daylight Autonomy plot for each blind control algorithm

3.3.2 Daylight Excessiveness (ASE)

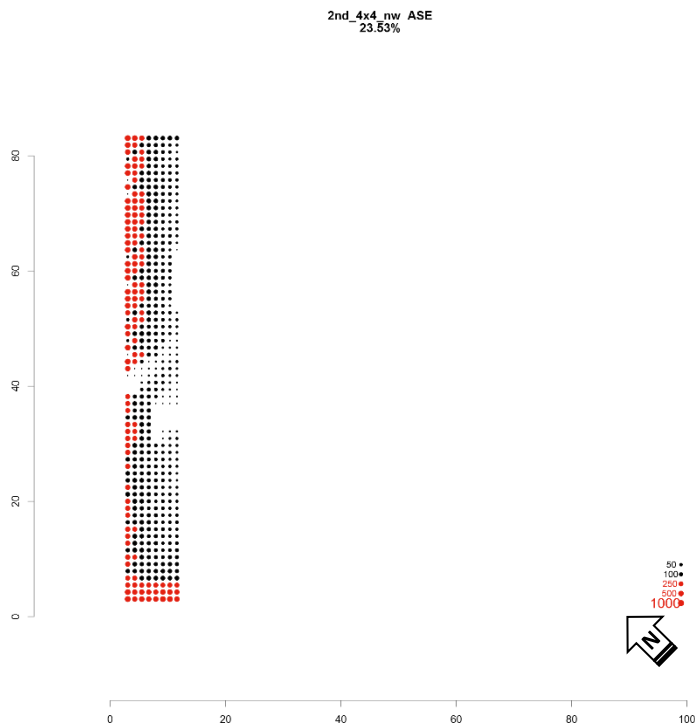
As it was mentioned in methods section, according to IES LM-83 2012 documentation, analysis areas should not exceed 10,000 sf. Therefore, ASE calculated based on proposed daylight zones, monthly and annually as plotted in figures 3-22, 3-23, 3-24, 3-25; where the red dots are ASE above 250 hours (unacceptable area) and black dots are annual sunlight exposure below 250 hours (acceptable area) . Looking at plots below, North-east zone shows considerably lower values than other orientations. The highest amount of sunlight on North-east and North-west orientations reported during summer. In reverse, on South-east and South-west facades, winter has the highest ASE value.

The lowest ASE value is recorded in North-east zone with total 5.75% (minimum= 4.91% on January) while the highest ASE percentage is reported in South-west zone with total 41.72% (maximum= 68.13% on December). Finally all the daylighting zones were combined together for entire floor plate with total ASE value of 23.53% (Figure 3-26).



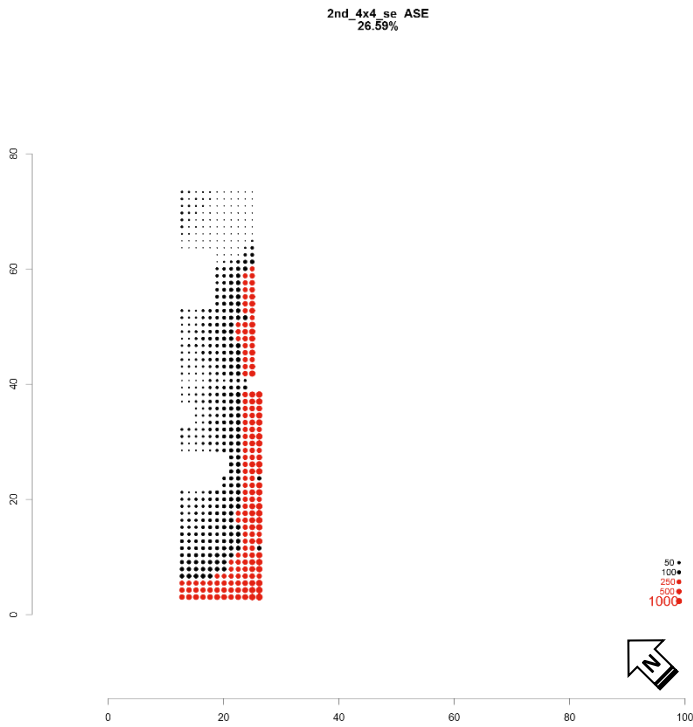
Zone	Time	% ASE
ne	Annual	5.75
ne	January	4.91
ne	February	5.08
ne	March	5.08
ne	April	8.46
ne	May	8.46
ne	June	11.00
ne	July	10.83
ne	August	9.64
ne	September	6.60
ne	October	6.26
ne	November	5.08
ne	December	6.60

Figure 3-22: Annual Sunlight Exposure (ASE) plot – North East daylight zone



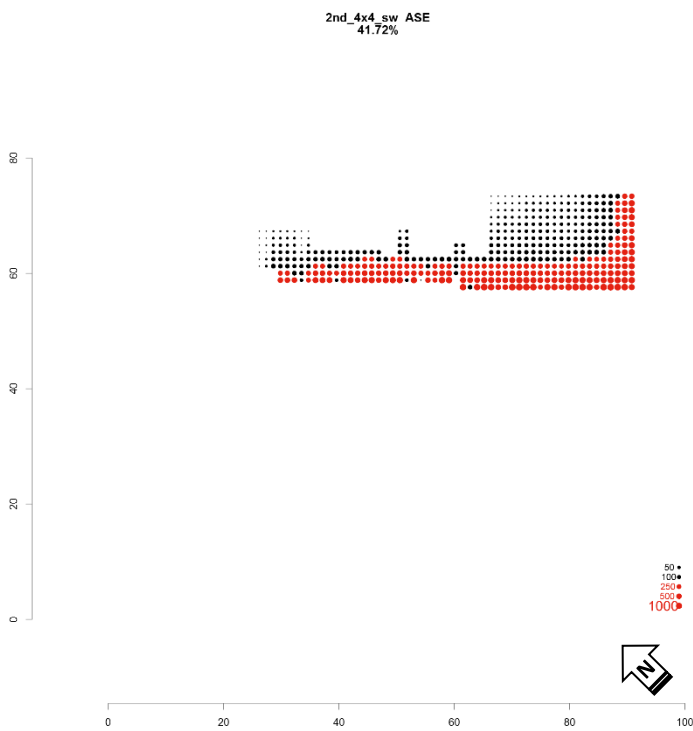
Zone	Time	% ASE
nw	Annual	23.53
nw	January	6.27
nw	February	10.20
nw	March	32.16
nw	April	27.65
nw	May	38.82
nw	June	38.24
nw	July	36.86
nw	August	41.57
nw	September	57.45
nw	October	20.98
nw	November	6.86
nw	December	8.04

Figure 3-23: Annual Sunlight Exposure (ASE) plot – North West daylight zone



Zone	Time	% ASE
se	Annual	26.59
se	January	38.13
se	February	39.80
se	March	31.44
se	April	19.57
se	May	11.37
se	June	10.37
se	July	11.04
se	August	18.06
se	September	28.60
se	October	38.63
se	November	41.97
se	December	49.50

Figure 3-24: Annual Sunlight Exposure (ASE) plot – South East daylight zone



Zone	Time	% ASE
sw	Annual	41.72
sw	January	60.59
sw	February	58.49
sw	March	39.62
sw	April	26.21
sw	May	17.40
sw	June	16.98
sw	July	17.19
sw	August	22.64
sw	September	35.01
sw	October	56.60
sw	November	61.84
sw	December	68.13

Figure 3-25: Annual Sunlight Exposure (ASE) plot – South West daylight zone

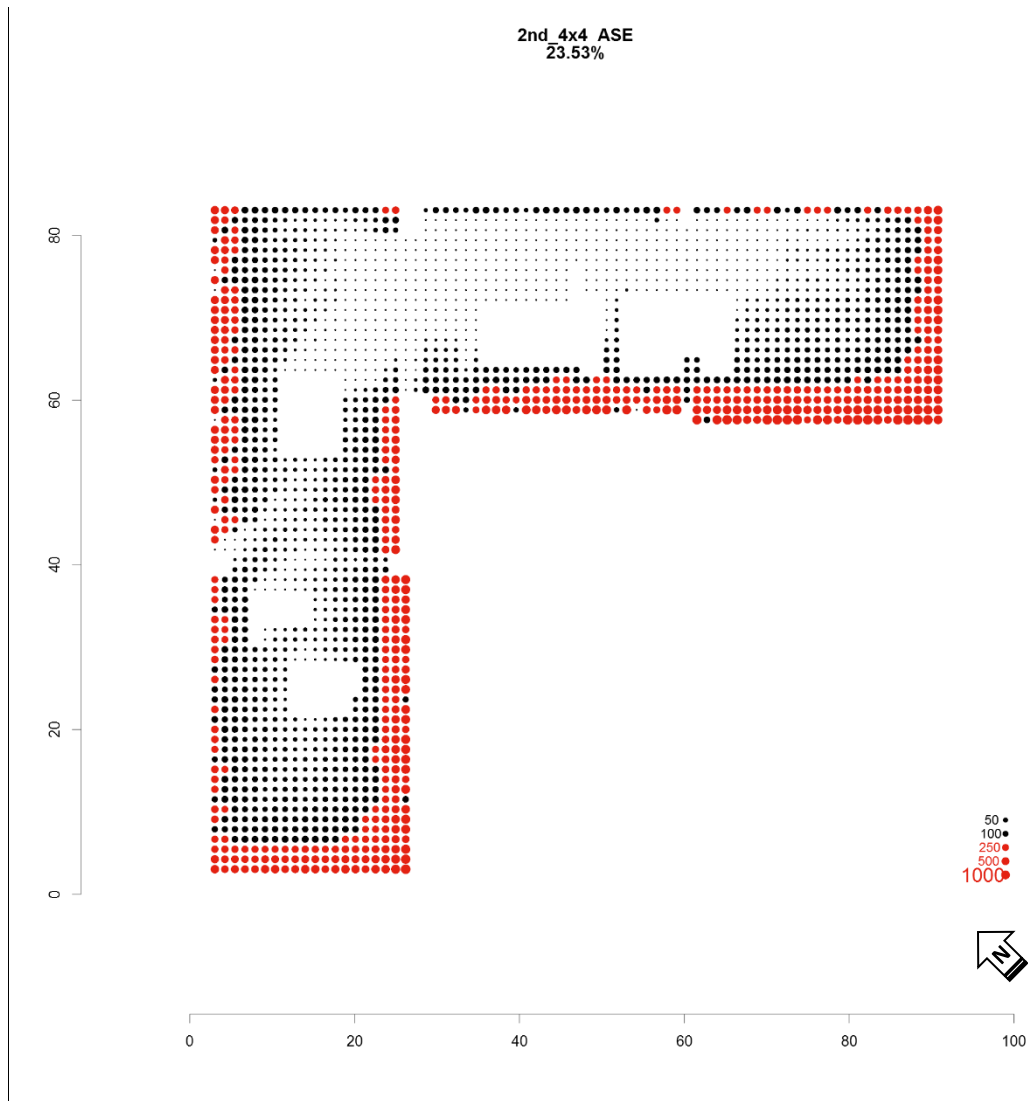


Figure 3-26: Annual Sunlight Exposure (ASE) plot – Entire Floor Plate

3.4 Annual Energy Consumption

Figure 3-27 and table 3-7, compare the annual energy use intensity (EUI) of all five manual and automated blind algorithms against a baseline which does not include blinds or daylight sensing lighting controls. Results are also shown relative to best- and worst-case scenarios, Always Retracted (Blinds open all the time and daylight harvesting controls added) and Always Engaged (Blinds closed all the time with daylight sensing lighting controls). The

blinds Always Retracted and Always Engaged algorithms show relative difference in total annual energy consumption of 16.42%. This suggests how significantly blinds impact whole building annual energy consumption. It is reported that total energy use of five strategies differed by approximately -11.7%, -13.7%, -13.8%, -10.4% and -11.4% using Blindswitch-A, Blindswitch-B, LM83, Automated Algorithm A and Automated Algorithm B respectively as compared to the baseline (Always retracted without lighting controls). Compared to the Always Retracted and Always Engaged baseline, the percentages vary from -1.6% (LM83) to -5.6% (Automated Algorithm A), and from -11.8% (Automated Algorithm A) to -15.1% (LM-83), respectively.

The five dynamic blind control algorithms also vary with respect to annual lighting end-use energy consumption; -59.8%, -65.0%, -65.9%, -58.3% and -65.0% using Blindswitch-A, Blindswitch-B, LM-83, Automated Algorithm A (BM-AAA) and Automated Algorithm B (BM-AAB) respectively versus the baseline which does not include blinds or daylight sensing lighting controls. While in comparison to the Always Retracted baseline, the difference ranges from -5.8% to -29.2% with the largest difference being Automated Algorithm A. Cooling consumption differences for the advanced blind control algorithms range from -0.6% (Blindswitch-B) to +3.6% (Automated Algorithm A), from -0.6% (Blindswitch-B) to +4.8% (Automated Algorithm A), and from -6.0% (Automated Algorithm A) to -9.7% (Blindswitch-B) compared to baseline model, Always Retracted and Always Engaged. For the baseline with blinds always open without daylight harvesting controls, heating end-use consumption differed by +5.5%, +4.8%, +4.3%, +6.7% and +9.6% using Blindswitch-A, Blindswitch-B, LM-83, Automated Algorithm A (BM-AAA) and Automated Algorithm B (BM-AAB) respectively. Amongst all five blind algorithms, Blindswitch-B

shows the lowest heating end-use (49.2 kWh/m²-yr), cooling end-use (16.7 kWh/m²-yr), while the lowest electrical lighting end-use (12.7 kWh/m²-yr) and overall energy consumption with 133.23 kWh/m²-yr (42.23 kBtu/ft²-yr) belongs to LM83-based manual blind use algorithm. End-uses such as fans, pumps and heat rejection were combined into one category, named other equipment. By applying blind algorithms, other equipment energy consumption more or less changed due to fans and pumps associated with shifted heating and cooling loads.

Looking at figure 3-27 and table 3-7, results were also compared based upon exterior and interior blinds for all five algorithms and Always Engaged. In general, exterior blinds block solar heat loads before they ever reach the window in this scenario. Accordingly, cooling end-use energy consumption significantly decreased (specifically during summer-time), ranging from a 9.5% to 26.5% reduction compared to interior blinds results. Conversely, heating end use increased by using blinds outside the building, but not substantially, in range 0.4% (Blindswitch-B) – 4.7% (Blind Manufacturer-Automated Algorithm B). The largest impact of switching from internal blinds to external blinds was seen in Always Engaged total energy result from 156.90 kWh/m²-yr to 144.59 kWh/m²-yr (-7.8% difference), while IES-LM-83 manual blind algorithm reveals the lowest difference in overall energy consumption by only 2.1 % reduction form interior to exterior.

Table 3-7: Annual end-use energy consumption comparison of five manual and automated blind algorithms

	Other Equip.	Delta	Heating	Delta	Cooling	Delta	Lighting	Delta	Total EUI (kWh/m ² -yr)	Total Delta
Baseline (without lighting controls)	53.7	-	46.9	-	16.8	-	37.1	-	154.52	-
Always retracted	54.2	100.8%	48.4	103.1%	16.6	99.3%	12.0	32.2%	131.13	84.9%
Always Engaged (Interior)	57.4	106.8%	47.9	102.2%	18.5	110.4%	33.1	89.2%	156.90	101.5%
Always	50.5	93.9%	49.4	105.3%	13.6	81.1%	31.1	83.9%	144.59	93.6%

Engaged (Exterior)										
Blindswitch-A (Interior)	55.1	102.5%	49.5	105.5%	16.9	101.0%	14.9	40.2%	136.39	88.3%
Blindswitch-A (Exterior)	50.8	94.5%	50.8	108.4%	13.9	83.1%	14.9	40.2%	130.46	84.4%
Blindswitch-B (Interior)	54.5	101.4%	49.2	104.8%	16.7	99.7%	13.0	35.0%	133.38	86.3%
Blindswitch-B (Exterior)	52.6	97.9%	49.4	105.3%	13.6	81.1%	13.0	35.0%	128.6	83.2%
LM-83 (Interior)	54.8	101.9%	48.9	104.3%	16.9	100.8%	12.7	34.1%	133.23	86.2%
LM-83 (Exterior)	53.3	99.1%	49.3	105.0%	15.3	91.5%	12.7	34.1%	130.50	84.5%
Automated Algorithm A (Interior)	55.5	103.3%	50.0	106.7%	17.4	103.7%	15.5	41.7%	138.41	89.6%
Automated Algorithm A (Exterior)	53.1	98.8%	50.8	108.2%	15.7	93.8%	15.5	41.7%	135.02	87.4%
Automated Algorithm B (Interior)	55.2	102.8%	51.4	109.6%	17.3	103.1%	13.0	35.0%	136.87	88.6%
Automated Algorithm B (Exterior)	53.3	99.2%	49.0	104.5%	15.7	93.7%	13.0	35.0%	131.00	84.8%

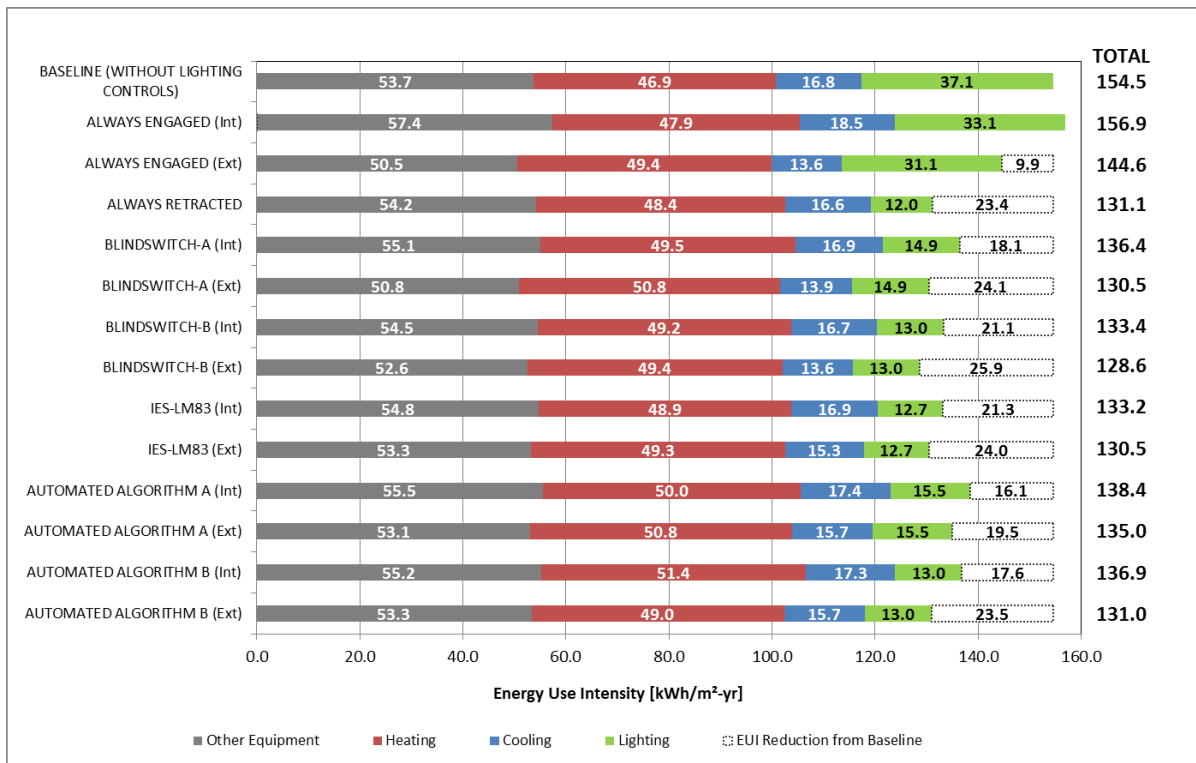


Figure 3-27: Annual end-use energy consumption comparison of five manual and automated blind patterns (interior/exterior)

4. Discussions and Conclusions

This research presented descriptive results in comparing relative differences between five leading candidate manual blind use and automated blind control algorithms, Blindswitch-A, Blindswitch-B, LM-83-based algorithm (manual blind algorithms), Blind Manufacturer-Automated Algorithm A (BM-AAA) and Blind Manufacturer-Automated Algorithm B (BM-AAB) (automated blind algorithms). The blind control algorithm clearly has an impact on both annual daylight performance and annual energy consumption. Furthermore, depending on if a, and if so which, manual blind use algorithm is implemented for daylighting and energy simulation, the results vary widely. It is reported that annual lighting end-use energy consumption of the three manual blind use algorithms differed by approximately -24.2%, -8.3% and -5.8% using Blindswitch-A, -B and LM-83 respectively as compared to a baseline with blinds always retracted with daylight sensing lighting controls; while the percentages are more or less in the same range for Blind Manufacturer-Automated Algorithm A (BM-AAA) and Blind Manufacturer-Automated Algorithm B (BM-AAB) with -29.2% and -8.3% respectively. For the same baseline, heating end-use consumption differed by +2.4%, +1.7%, +1.1%, +3.5% and +3.9% using Blindswitch-A, -B, LM-83, Blind Manufacturer-Automated Algorithm A (BM-AAA) and Blind Manufacturer-Automated Algorithm B (BM-AAB) respectively. Cooling consumption differences for the advanced blind control algorithms range from -0.6% (Blindswitch-B) to +3.6% (Automated Algorithm A), from +0.6% (Blindswitch-B) to +4.8% (Automated Algorithm A) and from -6.0% (Automated Algorithm A) to -9.7% (Blindswitch-B) compared to baseline model (Always retracted without lighting controls), Always Retracted and Always Engaged. Total energy use also differs dramatically based upon operation of blind control algorithms: -11.7%, -13.7%, -13.8%, -10.4% and -

11.4% using Blindswitch-A, Blindswitch-B, LM83, Automated Algorithm A (BM-AAA) and Automated Algorithm B (BM-AAB) respectively as compared to the baseline (Always retracted without lighting controls). Compared to the Always Retracted and Always Engaged, the percentages vary from +1.6% (LM83) to +5.6% (Automated Algorithm A), and from -11.8% (Automated Algorithm A) to -15.1% (LM83), respectively.

It is surprising that the automated control algorithms do not show more substantial daylighting improvement or annual energy savings compared to the manual controls. Some of this may be due to the simplifications required to enact these co-simulations in RADIANCE and EnergyPlus. Furthermore, it is likely that the manual blind use algorithms are still too much like an automated controller and not enough like the way people would really use manual blinds. Automated blind control algorithms (Automated Algorithm A (BM-AAA) and Automated Algorithm B (BM-AAB)) show the highest cooling end-use, heating energy use; while the highest electric lighting end use and the highest overall energy consumption belongs to Automated Algorithm A only. Amongst three candidates of manual blind use algorithms, the highest energy end-uses (heating, cooling and lighting) are recorded for Blindswitch-A. Furthermore, any energy design or operation decisions based upon end-use data are likely to be erroneously informed by end-use data provided without accurate manual blind operation algorithms. To our knowledge, no energy simulation calibration methods, energy code performance-based compliance methods or energy reach codes (until LEED V.4) require blind control algorithms (manual and automated) be implemented.

This paper has also provided inclusive results for the effect of blind control algorithms (manual and automated) on annual daylight sufficiency calculations such as spatial Daylight Autonomy. As it was expected, in general automated blind control algorithms show the

highest frequently blind movement (ROC and NBM) and the lowest percentages of blind closure compared to manual blind algorithms (except LM-83). However, in manual blind algorithms, Blindswitch-A shows the highest rate of change of blind position (ROC), the highest number of blind movements for those blinds that moved on a given day (NBM), the highest overall average blind occlusion during “occupied hours”, and therefore it is not surprising, to have the lowest spatial Daylight Autonomy (sDA) values. While, in reverse, too low blind occlusion percentages were reported for LM83-based algorithm. This leads to the conclusion that sophisticated manual blind use algorithms vary substantially from each other according to their logic. In this study, Blindswitch-A estimates that occupants mostly tend to leave the blinds closed, whereas LM83 assumes that retracted blind is the favourite position of blinds for occupants. However, there are still questions about which candidate manual blind use algorithm is most representative of actual user behaviour. The average of blind occlusion is notably lower for LM-83, and the values reported for Blindswitch-A and -B are more in line with some previous literature (Lindsay & Littlefair 1992; Sze 2009), but it is clear that additional human factors research is warranted in this area.

In annual sunlight exposure (ASE) metric, there is nothing that would suggest a difference depending on blind algorithms. While automated control algorithms should perhaps not be considered the same way as the manual algorithms, or should be given some sort of allowance that manual algorithms do not.

We propose several major outcomes and next steps:

- (1) Manual blind use patterns have considerable impact on energy end-use consumption and should be included (at least as a baseline) in building energy simulation, similar to Dyke et al. (2015). This is critically important to any simulation

reporting effects associated with automated blinds controls as impact relative to a baseline with manual lighting controls will be substantially different than a baseline with no blind use considered.

- (2) Blind study shows that current manual blind algorithms have unrealistically high values in number of blind movements and rate of change than what is generally expected from a manual blind. Also, in all three manual blind use algorithms, blind movements were recorded during unoccupied hours, which is not likely to happen in reality. Accordingly, adaptation of manual blind use algorithms to more realistic occupancy patterns (morning/lunch hour/afternoon) is needed as suggested by figure 3-28 (Duarte et al. 2013).

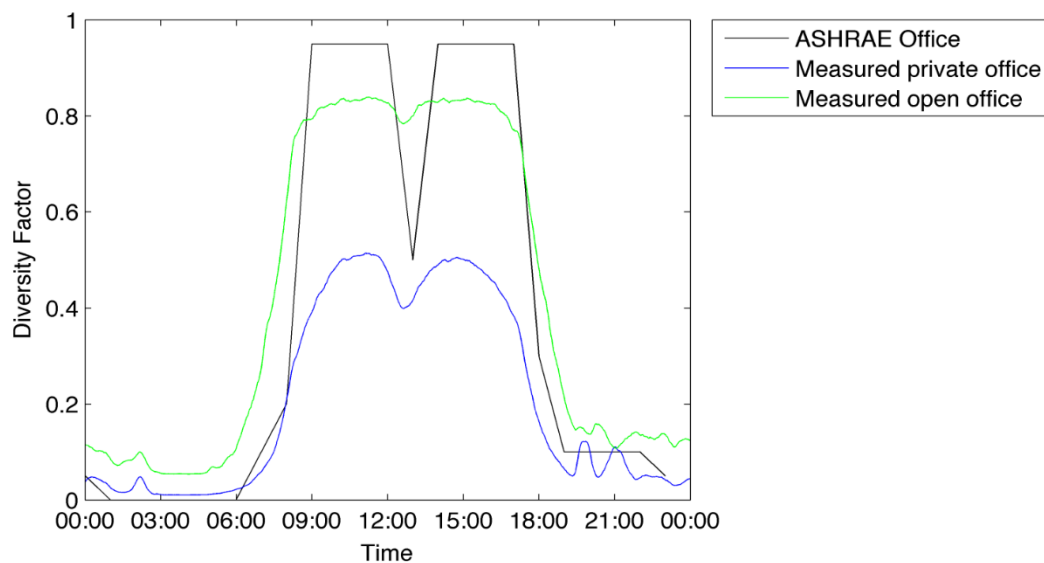


Figure 3-28: Occupancy schedule comparison in office spaces (Duarte et al. 2013)

- (3) Ideally, blinds are only deployed during direct sunlight and glare scenarios, and they are retracted immediately following to take advantage of the natural daylight and views. This can be achieved with automated blinds. Often, when left to manual operations, blinds are left deployed for the remainder of the day or longer. But this

study reveals that current candidate manual blind use patterns perform relatively similar to automated blinds, and surprisingly sometimes even more efficient; i.e. low blind occlusion values (LM83), high number of blind movement and rate of change (Blindswitch-A) and more energy saving. This could be somehow due to the 30 to 60 minute timesteps for the hysteresis in Blindswitch-A and Blindswitch-B account for some delay, but not much more, if any more, than what is forced upon the two automated algorithms due to the 1 hour simulation time steps. Running simulations at a finer timestep would allow for more savings to be found by the automated algorithm relative to the baseline. Furthermore, it is reasonable to also consider the always engaged baseline for results comparison with automated blinds.

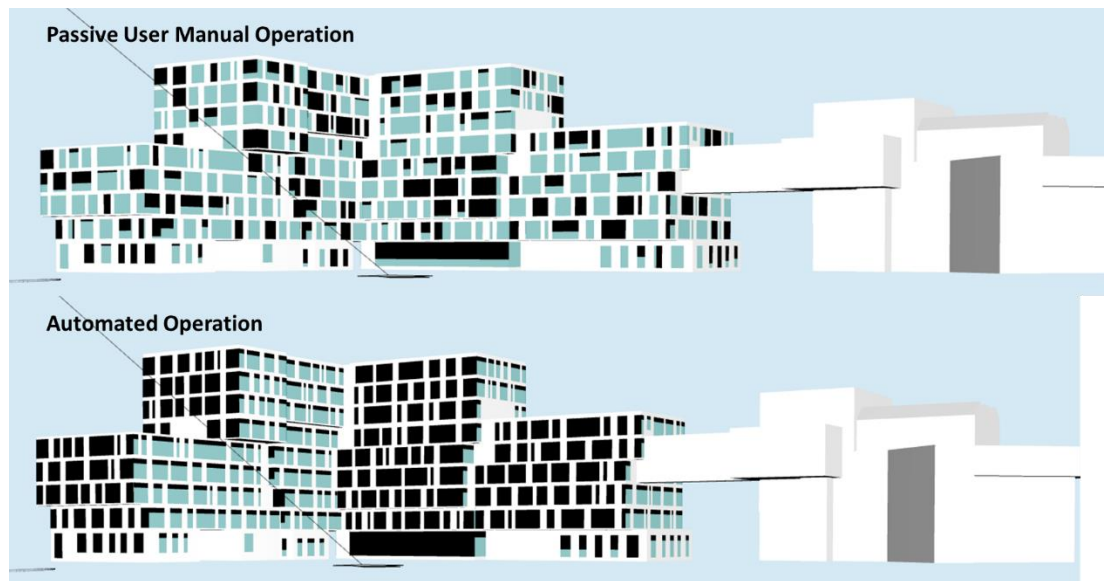


Figure 3-29: Blind Movement Comparison: Passive User Manual Operation Blind versus Automated Operation Blind on January 4th at 2PM.

- (4) The LM-83-based manual control algorithm notably has the lowest blind occlusion percentage with high NBM values. Furthermore, in the implementation of this algorithm, it was found that all details of the control logic are not spelled out in the

IES- DMC documentation of LM-83 (2012). Specifically, we decided to implement at worst-offender first approach to achieve less than 2% of sensors exceeding 1000 lux whereas others have implemented an approach to sequentially close all East, then South, then West then North windows (Heschong Mahone Group 2012) or an optimized approach that closes the minimum window area necessary to meet the performance criteria threshold (Mistrick, Daysim PS, TBD). It was also discovered that the size and shape of the analysis grid substantially impacts the LM-83 2% trigger, especially with larger spaces with multiple orientations, such as a whole floor plate. These details will be described in a future publication as well as recommended practice for the proper application of IES-LM-83.

- (5) In order to develop a consensus-based manual blind use algorithm for future use in simulation broadly, and energy codes, reach codes, and daylighting standards specifically, additional human factors and post occupancy research of manual blind use in real buildings is needed to support selection or refinement of current leading candidate algorithms. This study suggests that even the sluggish manual blind use algorithm is perhaps still too active (Blindswitch-A), however it is clear that the LM-83 algorithm is performing too much like, and in some cases better than, automated control algorithms in terms of annual daylight in and energy performance.
- (6) This paper presents a comparison of three candidates manual blind use algorithms for one office building in Boise, ID. Although these results can reasonably be extended to other regularly occupied open office workspaces with similar spatial configurations, in order to achieve more generalizable results, additional evaluations

of the impact within multiple climate zone and building shape and daylighting designs is warranted.

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APPENDIX A: EXEMPT CERTIFICATION FOR IRB PROJECT 15-724

The research protocol (project 15-724) was reviewed by the Institutional Review Board at the University of Idaho and was certified as exempt.

University of Idaho

Office of Research Assurances
Institutional Review Board

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To: Kevin Van Den Wymelenberg

From: Jennifer Walker
Chair, University of Idaho Institutional Review Board
University Research Office
Moscow, ID 83844-3010

Date: 5/27/2015 9:15:02 AM

Title: Daylight and visual comfort qualitative evaluation

Project: 15-724

Certified: Certified as exempt under category 4 at 45 CFR 46.101(b)(4).

On behalf of the Institutional Review Board at the University of Idaho, I am pleased to inform you that the protocol for the above-named research project has been certified as exempt under category 4 at 45 CFR 46.101(b)(4).

This study may be conducted according to the protocol described in the Application without further review by the IRB. As specific instruments are developed, modify the protocol and upload the instruments in the portal. Every effort should be made to ensure that the project is conducted in a manner consistent with the three fundamental principles identified in the Belmont Report: respect for persons; beneficence; and justice.

It is important to note that certification of exemption is NOT approval by the IRB. Do not include the statement that the UI IRB has reviewed and approved the study for human subject participation. Remove all statements of IRB Approval and IRB contact information from study materials that will be disseminated to participants. Instead please indicate, 'The University of Idaho Institutional Review Board has Certified this project as Exempt.'

Certification of exemption is not to be construed as authorization to recruit participants or conduct research in schools or other institutions, including on Native Reserved lands or within Native Institutions, which have their own policies that require approvals before Human Subjects Research Projects can begin. This authorization must be obtained from the appropriate Tribal Government (or equivalent) and/or Institutional Administration. This may include independent review by a tribal or institutional IRB or equivalent. It is the investigator's responsibility to obtain all such necessary approvals and provide copies of these approvals to ORA, in order to allow the IRB to maintain current records.

As Principal Investigator, you are responsible for ensuring compliance with all applicable FERPA regulations, University of Idaho policies, state and federal regulations.

This certification is valid only for the study protocol as it was submitted to the ORA. Studies certified as Exempt are not subject to continuing review (this Certification does not expire). If any changes are made to the study protocol, you must submit the changes to the ORA for determination that the study remains Exempt before implementing the changes. Should there be significant changes in the protocol for this project, it will be necessary for you to submit an amendment to this protocol for review by the Committee using the Portal. If you have any additional questions about this process, please contact me through the portal's messaging system by clicking the 'Reply' button at either the top or bottom of this message.

Jennifer Walker

APPENDIX B: SURVEY FORMS (Chapter 1 and 2)

B-1- Daylit Area Drawing Survey

Building Experience pg 1 of 6

Your Name: _____	Space Description: _____
Building Name: _____	Date: _____
City: _____	Time: _____
	Sky Condition: _____

“A key architectural concept is to divide the floor plan of a building or space into a ‘daylit’ and a ‘non-daylit’ area. Within the daylit area indoor illuminance levels due to natural light should be adequate, useful and balanced for most of the year. In this exercise you are asked to follow your own intuition and divide the ‘taped’ area of the study space into a daylit and a non daylit area. Please visit the study space during the field trips and individually conduct your assessment without consulting with the other students. During your visit you will be asked to carry out a series of illuminance measurements and to mark the daylit area on a floor plan of the space that you will be given.” [18 institution MIT led study]

Step 1 – The electric lighting in the study space should be switched off and any movable shading systems such as blinds should be fully retracted or opened. (If there are automated shading systems, they may remain in their automatically controlled position.) Turn off the electric lights as feasible and allowable and open blinds as feasible and allowable. Be sure to gain permission before turning off lights or adjusting blinds.

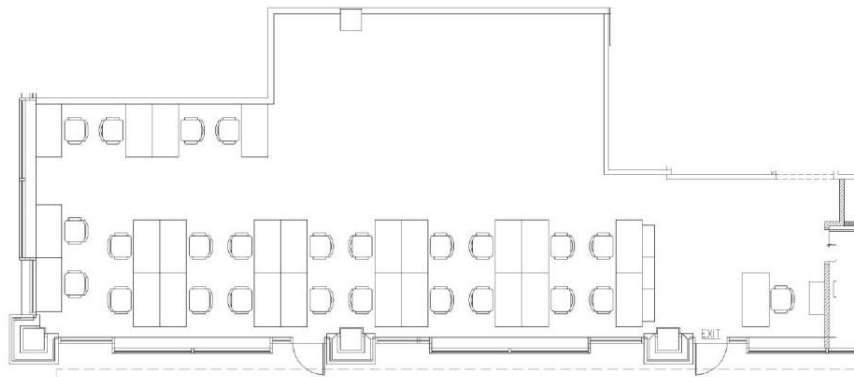
Step 2 – With electric lights off and manual blinds open, examine the space and its daylighting design. Do not consult with other students.

Step 3 – Draw a boundary between the ‘daylit’ and ‘non-daylit’ areas on the floor plan provided.

Step 4 – Record illuminance readings next to the floor plan (30” AFF) with the illuminance meter provided.

Step 5 – Complete the questionnaire on pages 2-4.

Step 6 – Complete a visual comfort evaluation for all “stations” established (likely four stations) using pages 5-6.



B-2- Questionnaire Survey

Building Experience pg 2 of 6

Your Name: _____
 Building Name: _____

Space Description: _____

Consider only the conditions present while assessment was made..

Strongly Disagree 1 2 3 4 5 6 7 8 9 Strongly Agree ___ n/a

1.	I enjoy being in this room.	□□□□□□□□□□	□
2.	I find this room visually attractive.	□□□□□□□□□□	□
3.	I like the view I have from the window.	□□□□□□□□□□	□
4.	I think the view from the window is big enough.	□□□□□□□□□□	□
5.	I am happy with how the blinds are positioned.	□□□□□□□□□□	□
<hr/>			
6.	The lighting conditions are comfortable.	□□□□□□□□□□	□
	7. SKIP.	□□□□□□□□□□	□
	8. SKIP.	□□□□□□□□□□	□
9.	I can work happily in this room under current lighting conditions.	□□□□□□□□□□	□
	10. SKIP.	□□□□□□□□□□	□
<hr/>			
11.	The daylight in this room is sufficient.	□□□□□□□□□□	□
12.	The daylight in this room is not too bright.	□□□□□□□□□□	□
13.	I am able to do my work here without any problems from daylight induced glare.	□□□□□□□□□□	□
	14. I like the Daylight Uniformity.	□□□□□□□□□□	□
	15. I like the vertical surface brightness.	□□□□□□□□□□	□
<hr/>			
16.	The computer screens are legible and free of veiling reflections.	□□□□□□□□□□	□
	17. I can see faces legibly in all directions.	□□□□□□□□□□	□
18.	I can control my visual conditions to maintain personal comfort.	□□□□□□□□□□	□
	19. There is no glare from daylight apertures.	□□□□□□□□□□	□
	20. There is no of glare from direct sun penetration.	□□□□□□□□□□	□
<hr/>			
21.	There is no veiling glare on white boards and displays.	□□□□□□□□□□	□
22.	I do not feel too hot due to being near the daylight apertures.	□□□□□□□□□□	□
23.	I do not feel chilled by being near the daylight apertures.	□□□□□□□□□□	□
24.	There is adequate acoustic privacy within the space.	□□□□□□□□□□	□
25.	There is adequate acoustic isolation from outside noise.	□□□□□□□□□□	□

Building Experience pg 3 of 6

Your Name: _____
 Building Name: _____

Space Description: _____

Consider the whole space over the entire year and all sky conditions.

Strongly Disagree 1 2 3 4 5 6 7 8 9 Strongly Agree n/a

1.	I enjoy being in this room.	□□□□□□□□	□
2.	I find this room visually attractive.	□□□□□□□□	□
3.	I like the view I have from the window.	□□□□□□□□	□
4.	I think the view from the window is big enough.	□□□□□□□□	□
5.	I am happy with how the binds/curtains can be operated.	□□□□□□□□	□
<hr/>			
6.	The lighting conditions are always comfortable.	□□□□□□□□	□
7.	The electric lights in this room are always sufficient.	□□□□□□□□	□
8.	The electric lights are never too bright or glary.	□□□□□□□□	□
9.	I can work happily in this room with SOME of the electric lights turned off.	□□□□□□□□	□
10.	I can work happily in this room with ALL the electric lights turned off.	□□□□□□□□	□
<hr/>			
11.	The daylight in this room is always sufficient.	□□□□□□□□	□
12.	The daylight in this room is never too bright.	□□□□□□□□	□
13.	I am able to do my work here without any problems from daylight induced glare.	□□□□□□□□	□
14.	I like the Daylight Uniformity.	□□□□□□□□	□
15.	I like the vertical surface brightness.	□□□□□□□□	□
<hr/>			
16.	The computer screens are legible and free of veiling reflections.	□□□□□□□□	□
17.	I can see faces legibly in all directions.	□□□□□□□□	□
18.	All occupants can control their visual conditions to maintain personal comfort.	□□□□□□□□	□
19.	There is low probability of glare from daylight apertures.	□□□□□□□□	□
20.	There is low probability of glare from direct sun penetration.	□□□□□□□□	□
<hr/>			
21.	There is low probability of veiling glare on white boards and displays.	□□□□□□□□	□
22.	There is low probability that some occupants will overheat near daylight apertures.	□□□□□□□□	□
23.	There is low probability that some occupants will be chilled near the daylight apertures.	□□□□□□□□	□
24.	There is adequate acoustic privacy within the space.	□□□□□□□□	□
25.	There is adequate acoustic isolation from outside noise.	□□□□□□□□	□

Building Experience pg 4 of 6

Your Name: _____
 Building Name: _____

Space Description: _____

Over the course of a day, do you think there will be sufficient daylight illumination in this space, for:

Insufficient Daylight 1 2 3 4 5 6 7 8 9 Sufficient Daylight n/a

- | | | | |
|-----|---------------------------------------|----------|---|
| 26. | Today' s weather conditions | □□□□□□□□ | □ |
| 27. | A summer (light) overcast day. | □□□□□□□□ | □ |
| 28. | A winter (heavy) overcast day. | □□□□□□□□ | □ |
| 29. | A sunny summer day. | □□□□□□□□ | □ |
| 30. | A sunny spring day. | □□□□□□□□ | □ |
| 31. | A sunny fall day. | □□□□□□□□ | □ |
| 32. | A sunny winter day. | □□□□□□□□ | □ |

Over the course of a day, do you think there will be glare or sun penetration problems in this space?

Serious Problem 1 2 3 4 5 6 7 8 9 No Problem n/a

- | | | | |
|-----|---------------------------------------|----------|---|
| 33. | Today' s weather conditions. | □□□□□□□□ | □ |
| 34. | A summer (light) overcast day. | □□□□□□□□ | □ |
| 35. | A winter (heavy) overcast day. | □□□□□□□□ | □ |
| 36. | A sunny summer day. | □□□□□□□□ | □ |
| 37. | A sunny spring day. | □□□□□□□□ | □ |
| 38. | A sunny fall day. | □□□□□□□□ | □ |
| 39. | A sunny winter day. | □□□□□□□□ | □ |

Rank any listed answers for each question.

40. Describe the best daylighting feature(s) in the space.

41. Describe the worst daylighting features and key sources of visual discomfort in the space.

42. How would you suggest the space' s daylighting could best be improved?

B-3- Demographics Questionnaire

The demographics questionnaire included the following items:

1. What is your gender?
2. What is your age?
3. What type of vision correction do you normally require?
4. What type of vision correction do you have today?
5. What is your eye color?
6. Do you have any type of color blindness?
7. Do you have any other vision related health issues? (If yes, please explain)
8. What time do you usually wake up?
9. What time did you wake up today?
10. In general, I am sensitive to glare?

APPENDIX C: STUDY SPACES (Chapter 1 and 2)

Daylit Drawings

Questionnaires

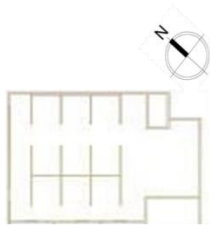


Figure C1: Space #01- Boise, ID – Open office space – 8th floor

Daylit Drawings

Questionnaires

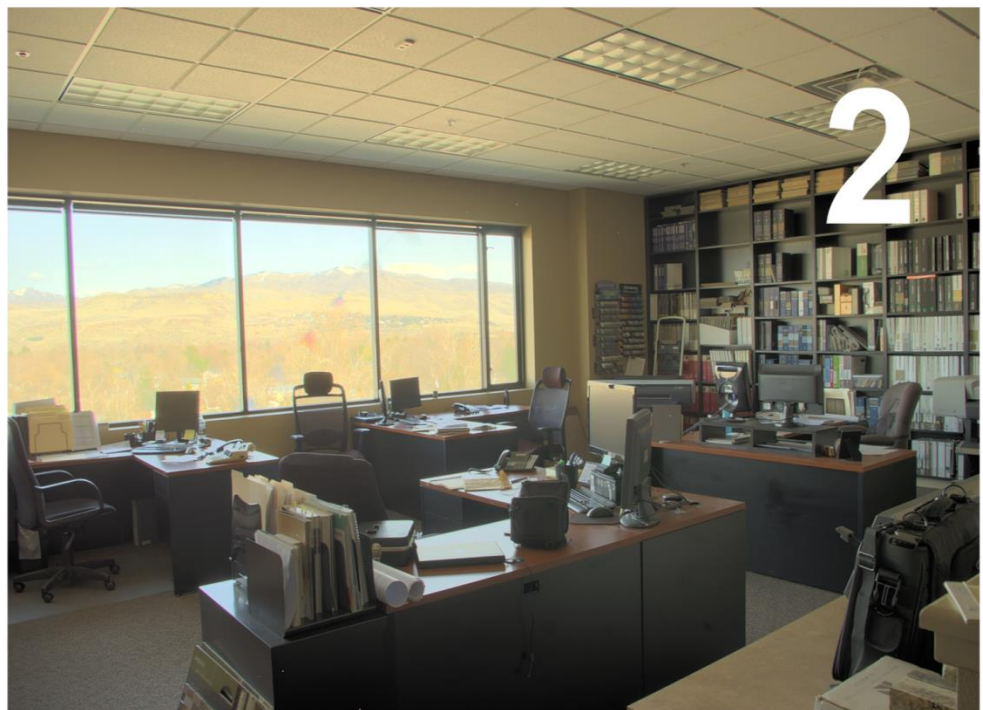
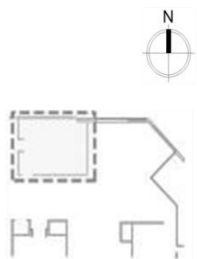


Figure C2: Space #02- Boise, ID – Open office space – 2nd Floor

- Daylit Drawings
- Questionnaires

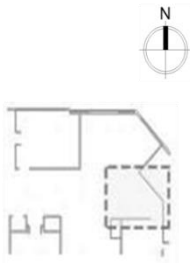


Figure C3: Space #03- Boise, ID – Reception space – 2nd Floor

- Daylit Drawings
- Questionnaires



Figure C4: Space #04- Boise, ID – Classroom – 1st Floor

Questionnaires

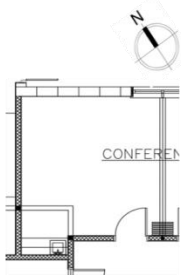


Figure C5: Space #05- Boise, ID – Conference Room – 1st Floor

Questionnaires

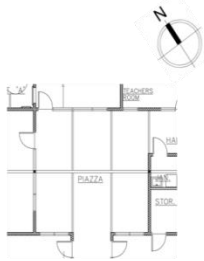


Figure C6: Space #06- Boise, ID – Atrium space – 1st Floor

- Daylit Drawings
- Questionnaires

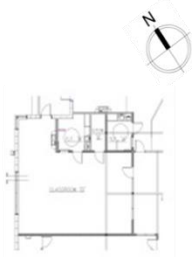


Figure C7: Space #07- Boise, ID – Open office space – 1st Floor

- Daylit Drawings
- Questionnaires

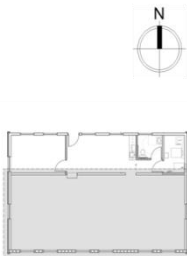


Figure C8: Space #08- Boise, ID – Open office space – 1st Floor

Daylit Drawings

Questionnaires



Figure C9: Space #09- Boise, ID – Meeting Room – 1st Floor

Daylit Drawings

Questionnaires



Figure C10: Space #10- Boise, ID – Classroom – 1st Floor

Daylit Drawings
Questionnaires



Figure C11: Space #11- Boise, ID – Open office space – 1st Floor

Daylit Drawings
Questionnaires

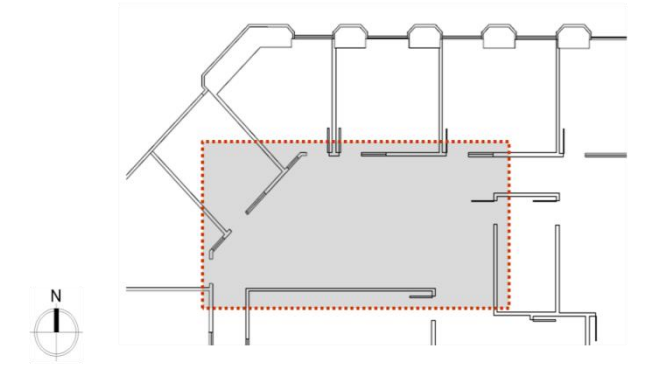
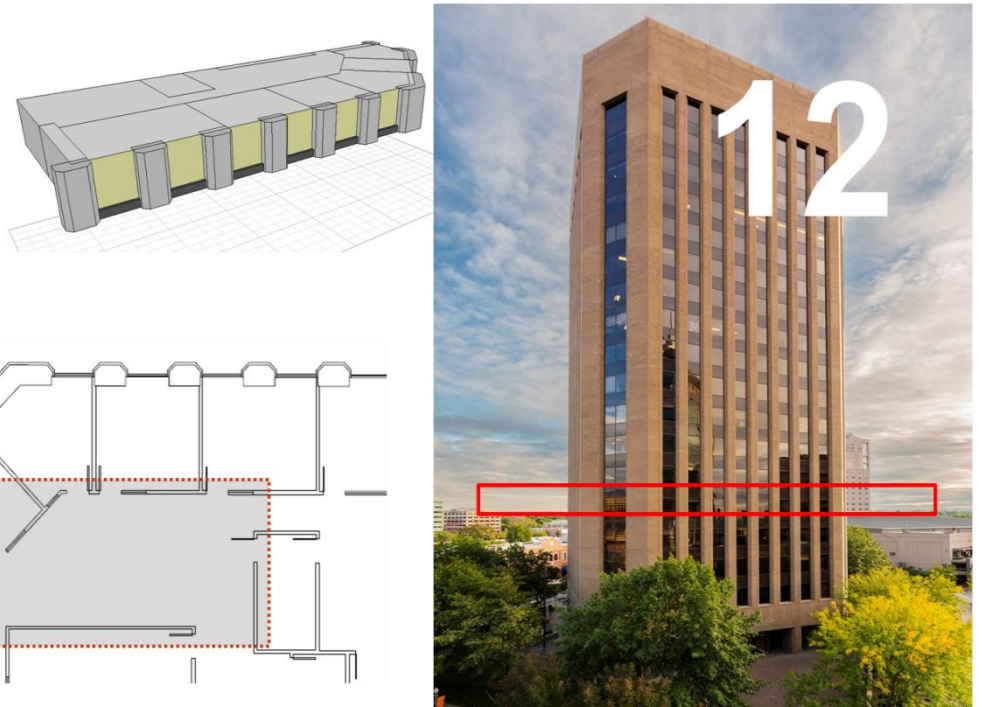


Figure C12: Space #12- Boise, ID – Open office space – 6th Floor

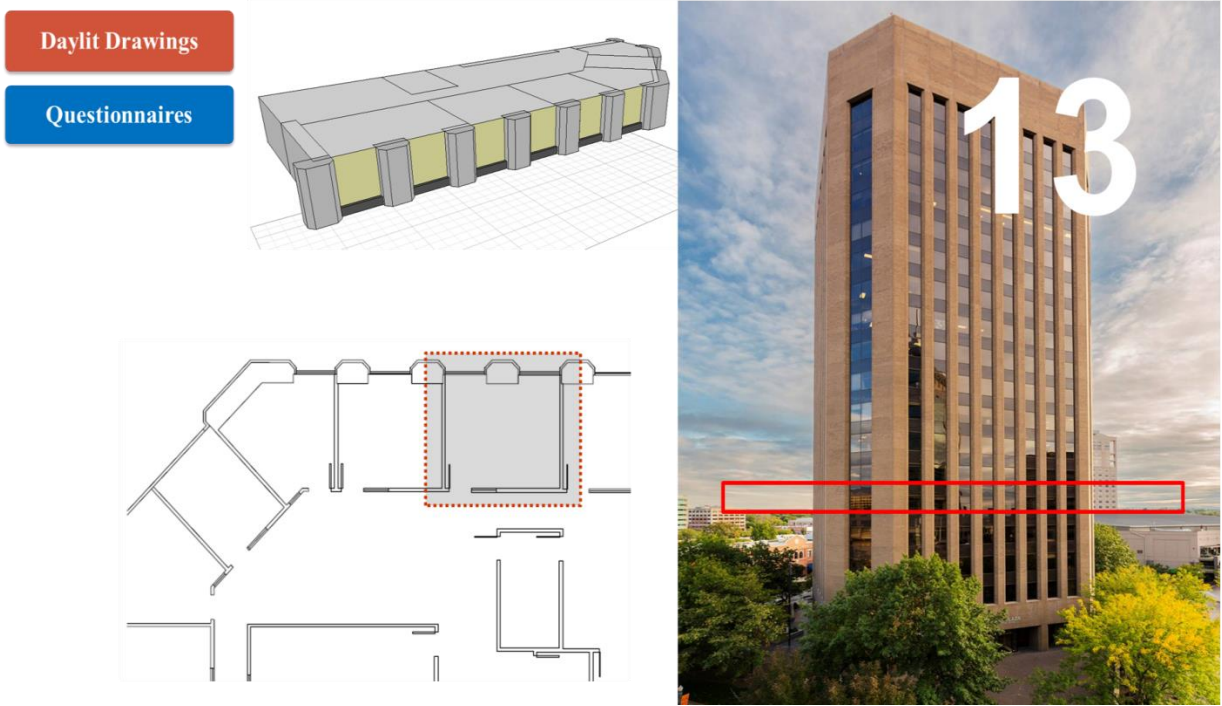


Figure C13: Space #13- Boise, ID – Private office space – 6th Floor

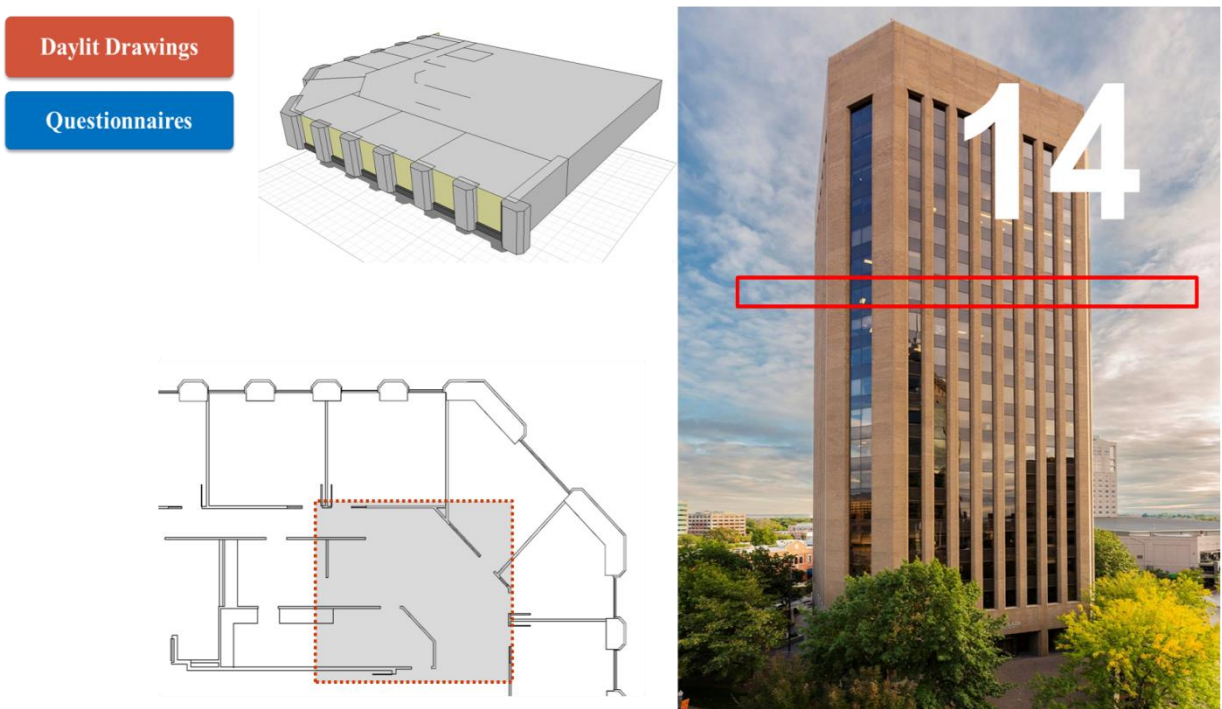


Figure C14: Space #14- Boise, ID – Open office space – 12th Floor

Daylit Drawings
Questionnaires

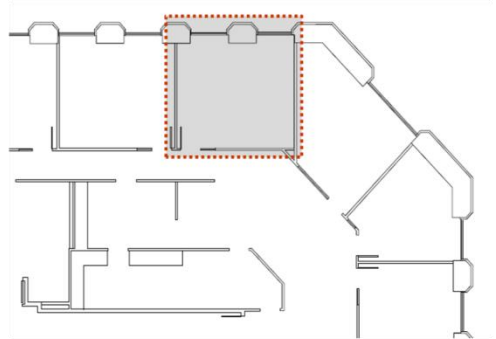
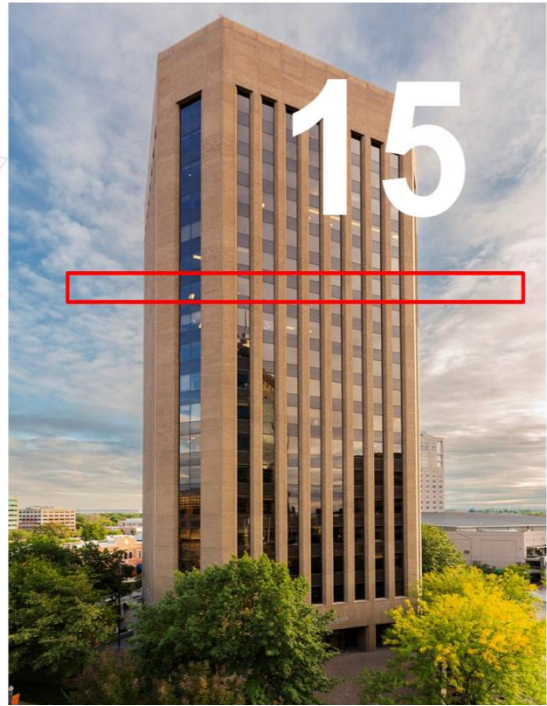
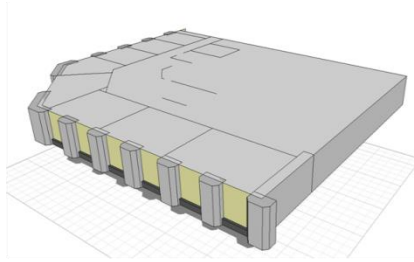


Figure C15: Space #15- Boise, ID – Private office space – 12th Floor

Questionnaires



Figure C16: Space #16- Boise, ID – Open office & Classroom – 1st Floor

Daylit Drawings
Questionnaires



Figure C17: Space #17- Boise, ID – Architecture studio space – 1st Floor

Questionnaires

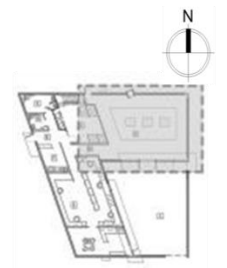


Figure C18: Space #18- Boise, ID – Gallery, main space – 1st Floor

Daylit Drawings
Questionnaires

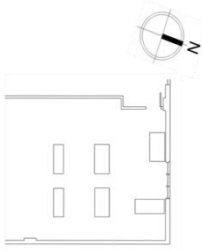


Figure C19: Space #19- Boise, ID – Open office space – 1st Floor

Questionnaires

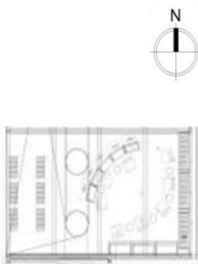


Figure C20: Space #20- Seattle, WA – Periodical reading room – 1st Floor

Questionnaires

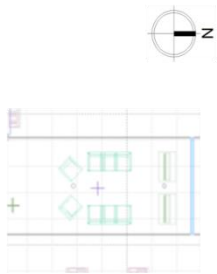


Figure C21: Space #21- Seattle, WA – Stacks reading room – 1st Floor

Daylit Drawings

Questionnaires

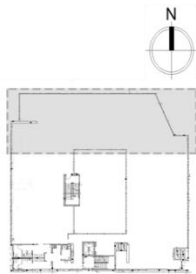
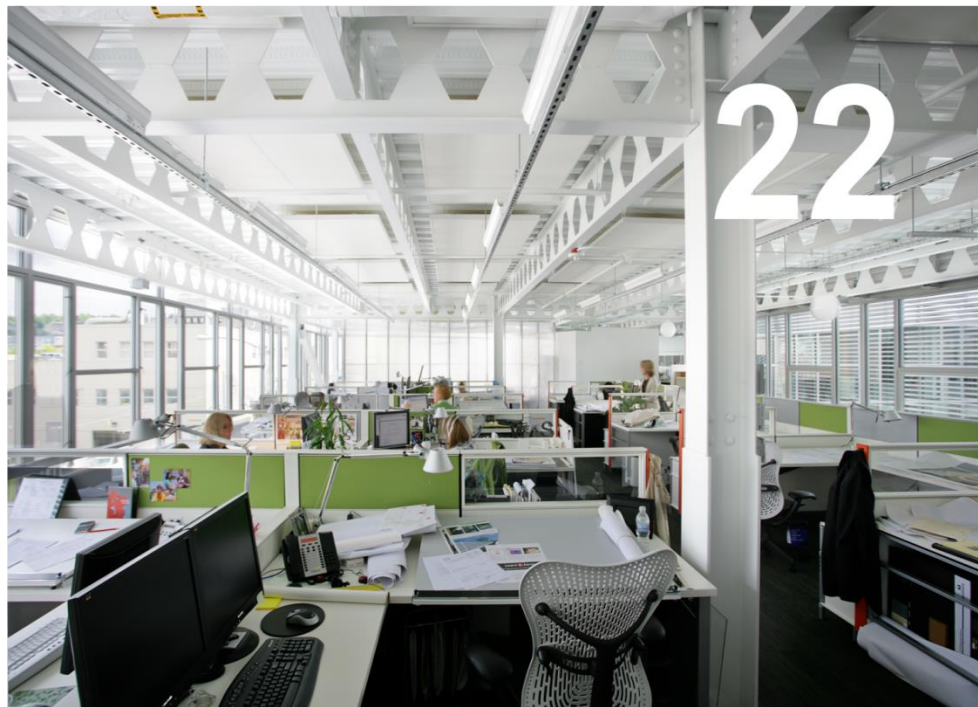


Figure C22: Space #22- Seattle, WA – Open office space – 2nd Floor

Daylit Drawings
Questionnaires

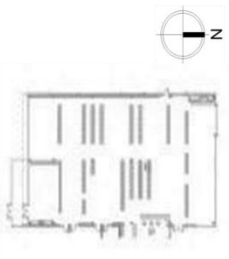


Figure C23: Space #23- Boise, ID – Library, main space – 1st Floor

Daylit Drawings
Questionnaires

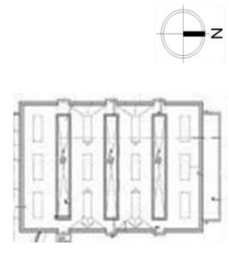


Figure C24: Space #24- Seattle, WA – Gymnasium – 1st Floor

APPENDIX D: STUDY SPACES – EXTERIOR OBSTRUCTION

Based on IES LM-83 (2012) documentation (section 2.2.8): “... Exterior obstructions are very common and have a profound effect on daylight availability, blocking direct sunlight and view of the sky dome, but also reflecting daylight to a façade...Exterior obstructions shall be modeled using at least 100’ of the spaces under study.” Accordingly, 24 study spaces within 14 buildings were double-checked with Google Earth and illustrated below.



Figure D1: Boise, ID – Space #01

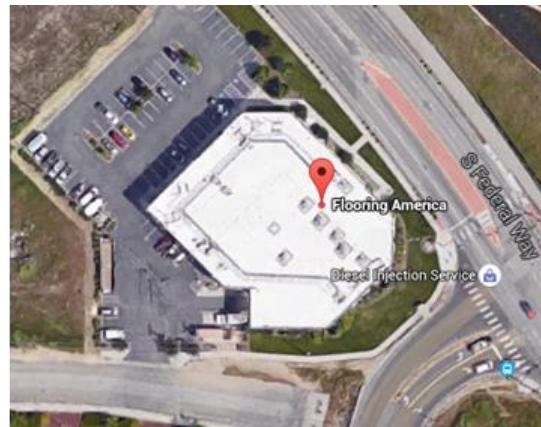


Figure D2: Boise, ID – Spaces #02 and 03



Figure D3: Boise, ID – Spaces #04, 05, 06 and 07



Figure D4: Boise, ID – Spaces #08 and 09

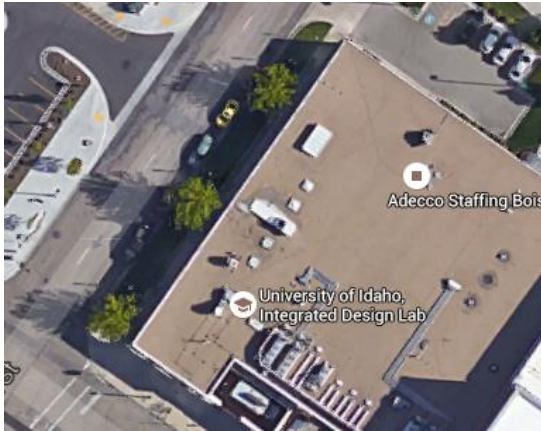


Figure D5: Boise, ID – Spaces #10 and 11

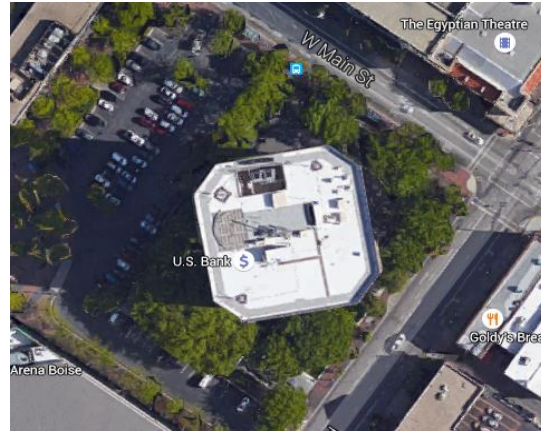


Figure D6: Boise, ID – Spaces #12, 13, 14 and 15

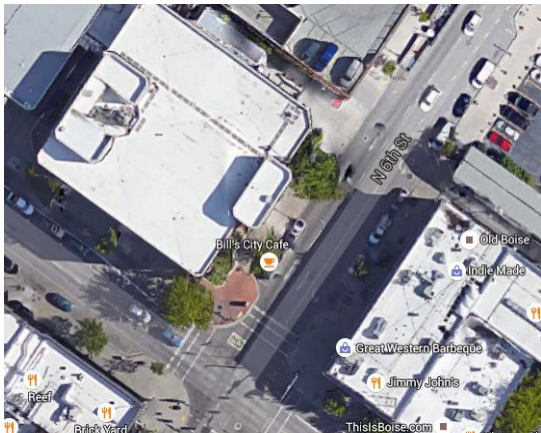


Figure D7: Boise, ID – Space #16

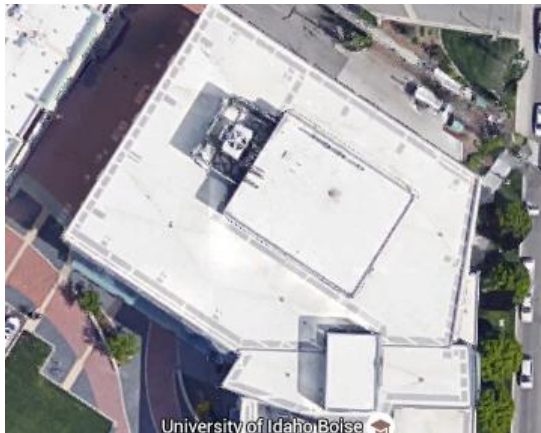


Figure D8: Boise, ID – Space #17



Figure D9: Boise, ID – Space #18

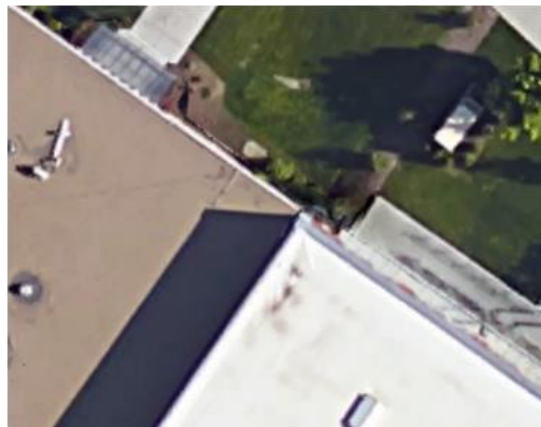


Figure D10: Boise, ID – Space #19



Figure D11: Boise, ID – Spaces #20 and 21

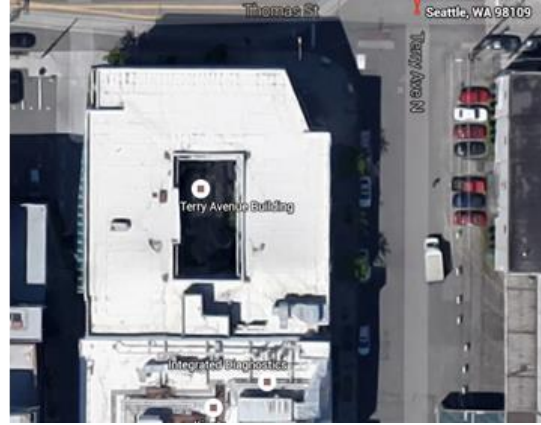


Figure D12: Boise, ID – Space #22



Figure D13: Boise, ID – Space #23



Figure D14: Boise, ID – Space #24

APPENDIX E: SIMULATION METHOD – MODELING FOR RADIANCE

1 - Starting from OpenStudio energy model.

Revit provides more detailed geometry, but also more potential for troubleshooting.

Gaps between the various geometries causes light leaks in RADIANCE.



Figure E1: OpenStudio Model

2 - Furniture and wall partitions were added in SketchUp as needed for daylight analysis.

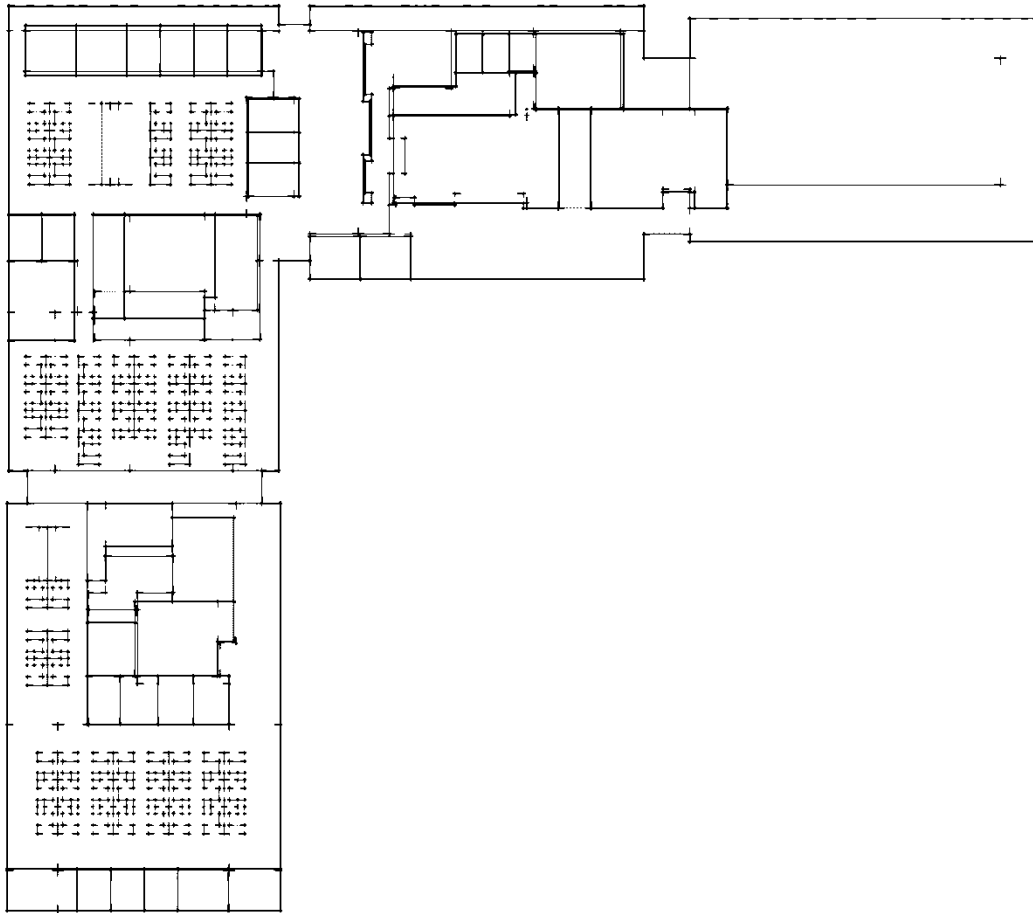


Figure E2: SketchUp model – Addition of furniture

3 - Export from SketchUp.

- Wavefront .OBJ
- Directly to .RAD via su2rad SketchUp extension.

```
# obj2rad -f usb.obj
# Alias OBJ Model File
# Exported from SketchUp, (c) 2000-2012 Trimble Navigation Limited
# File units = meters
OpenStudio_Floor_Ext polygon Mesh1.Group1.Model.1
0
0
18
7.04808      64.0353      0.0381
32.7513      64.0353      0.0381
32.7513      50.2002      0.0381
```

```

-1.5283    50.2002    0.0381
-1.5283    56.7708    0.0381
0.375115   57.2217    0.0381
# Done processing file: usb.obj
# 24 lines, 20 statements, 1 unrecognized

```

4- RAD/OBJ script-based analysis grid was generated, similar to Ecotect's tool, minus the interface.

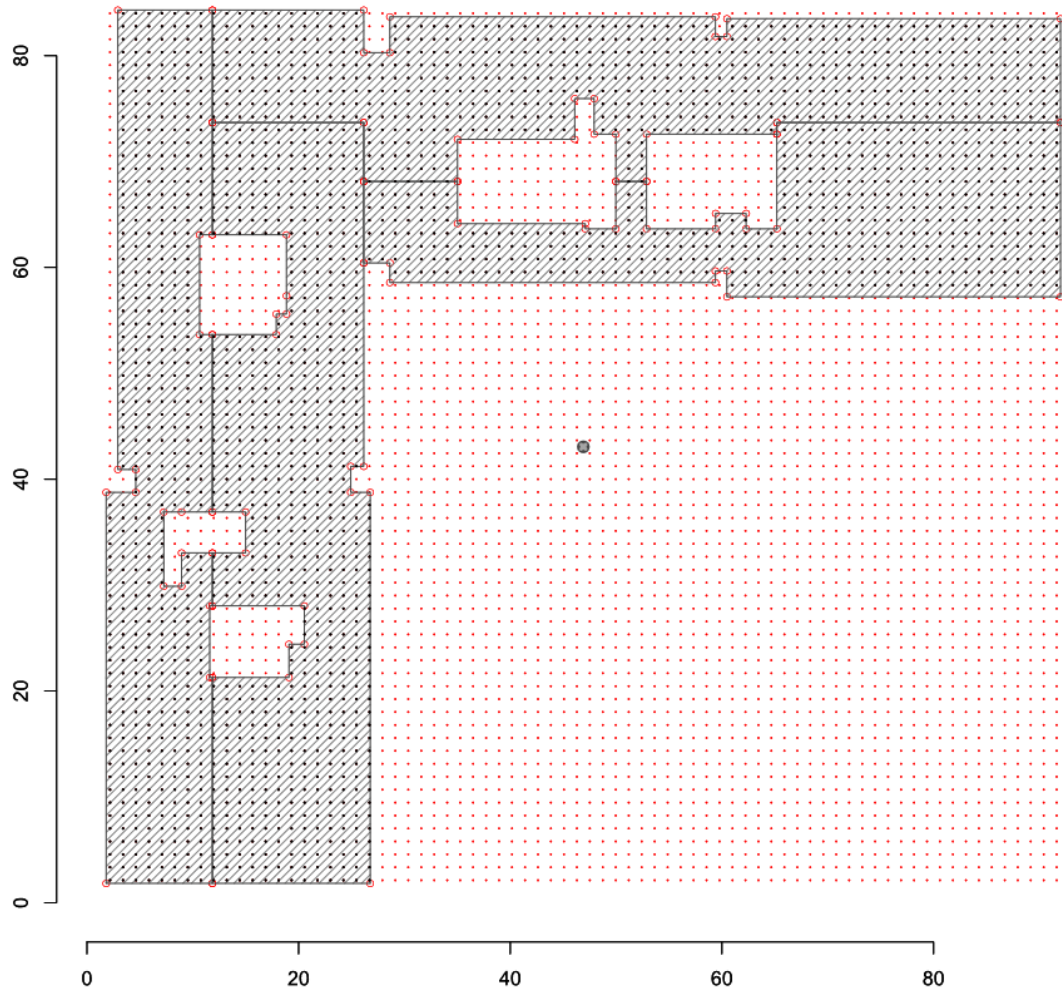


Figure E3: RAD/OBJ script-based analysis grid

5- Model organization for RADIANCE.

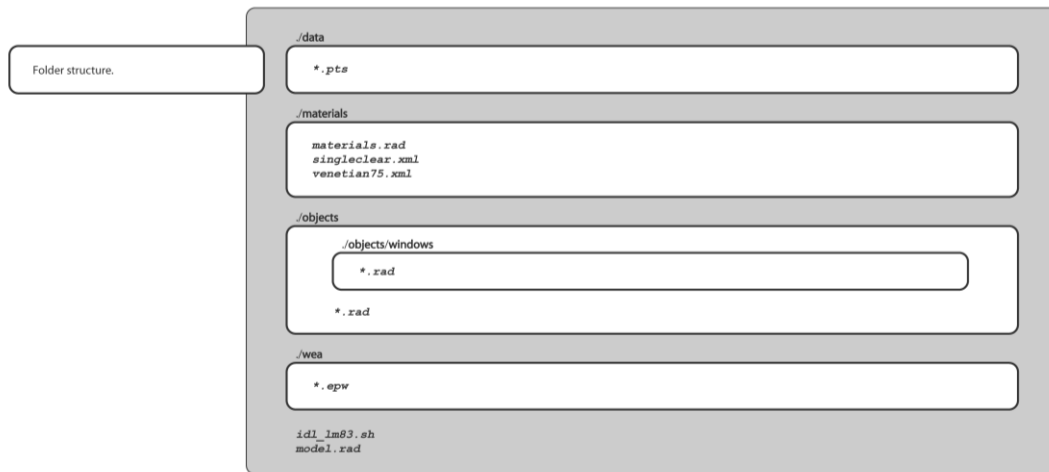


Figure E4: Model organization

6- Bidirectional Scattering Distribution Function (BSDF) was defined in LBNL Window7 BSRF calculation.

Glazing System Library

ID #: 15 Name: closed_5

Layers: 3 Tilt: 90 ° IG Height: 1000.0 mm

Environmental Conditions: NFRC 100-2010 IG Width: 1000.0 mm

Comment:

Overall thickness: 126.940 mm Mode: #

	ID	Name	Mode	Thick	Flip	Tsol	Rsol1	Rsol2	Tvis	Rvis1	Rvis2	Tir	E1	E2	Cond
▼ Glass 1 ▶▶	103	CLEAR_6.DAT	#	5.7	<input type="checkbox"/>	0.771	0.070	0.070	0.884	0.080	0.080	0.000	0.840	0.840	1.000
Gap 1 ▶▶	1	Air		12.7	<input type="checkbox"/>										
▼ Glass 2 ▶▶	5251	SB60 Starphire_8.PPG	#	7.9	<input type="checkbox"/>	0.413	0.387	0.455	0.808	0.057	0.049	0.000	0.838	0.035	1.000
Gap 2 ▶▶	1	Air		100.0	<input type="checkbox"/>										
▼ Shade 3 ▶▶	23	Generic Woven Shade 5%D		0.6	<input type="checkbox"/>							0.000	0.900	0.900	0.300

Center of Glass Results | Temperature Data | Optical Data | Angular Data | Color Properties

Ufactor	SC	SHGC	Rel. Ht. Gain	Tvis	Keff	Gap 1 Keff	Gap 2 Keff
W/m2-K			W/m2		W/m-K	W/m-K	W/m-K
1.810	0.381	0.331	251	0.187	0.2563	0.0634	0.3809

Figure E5: Define Bidirectional Scattering Distribution Function (BSDF) in LBNL Window7

APPENDIX F: BLINDSWITCH-2012A SAMPLE INPUT FILE

The code seen below is the updated version of the code proposed by Chris Dyke 2013². The code applies to 10 adjacent windows as a group (according to Blindswitch-A logic) on the north-east façade on the second floor. Two construction were defined: (1) Construction of the window without the shade, and reference it in the FenestrationSurface:Detailed object for each window separately. (2) Another construction was defined as “shaded construction” that includes the WindowMaterial:Shade object. WindowMaterial:Shade object specifies the properties of window shade materials. And finally, WindowProperty:ShadingControl object is needed to reference the shaded construction and specify how the shade is controlled.

Six of the windows (Windows 3-8) are considered operable (see Chapter 3), therefore there are only six control algorithms. Each algorithm, represented by the EnergyManagementSystem:Program object, contains the code for a manual blind control response. The same code, seen here, is applied to other window groups on each façade.

```
!- ===== ALL OBJECTS IN CLASS: CONSTRUCTION =====

Construction,
  CGP_Ext_Window1,    !- Name
  Clear 3mm,          !- Outside Layer
  000_Air 13mm,       !- Layer 2
  Clear 3mm,          !- Layer 3
  BLIND;              !- Layer 4

Construction,
  window_construction, !- Name
  Clear 3mm,           !- Outside Layer
  000_Air 13mm,       !- Layer 2
  Clear 3mm;          !- Layer 3

!- ===== ALL OBJECTS IN CLASS: WINDOWMATERIAL:BLIND =====

WindowMaterial:Blind,
```

² Dyke, C. A Comparison of Manual Blind Control Algorithms Using Two Methods of Daylight Harvesting Simulation. Master Thesis, University of Idaho, Moscow, ID, USA, May 2013.


```

BLIND,          !- Name
HORIZONTAL,     !- Slat Orientation
0.0508,        !- Slat Width {m}
0.0508,        !- Slat Separation {m}
0.001,         !- Slat Thickness {m}
15,           !- Slat Angle {deg}
0.1,          !- Slat Conductivity {W/m-K}
0.0,          !- Slat Beam Solar Transmittance
0.7,          !- Front Side Slat Beam Solar Reflectance
0.7,          !- Back Side Slat Beam Solar Reflectance
0.0,          !- Slat Diffuse Solar Transmittance
0.7,          !- Front Side Slat Diffuse Solar Reflectance
0.7,          !- Back Side Slat Diffuse Solar Reflectance
0.0,          !- Slat Beam Visible Transmittance
0.5,          !- Front Side Slat Beam Visible Reflectance
0.5,          !- Back Side Slat Beam Visible Reflectance
0.0,          !- Slat Diffuse Visible Transmittance
0.5,          !- Front Side Slat Diffuse Visible Reflectance
0.5,          !- Back Side Slat Diffuse Visible Reflectance
0.0,          !- Slat Infrared Hemispherical Transmittance
0.9,          !- Front Side Slat Infrared Hemispherical Emissivity
0.9,          !- Back Side Slat Infrared Hemispherical Emissivity
0.050,        !- Blind to Glass Distance {m}
0.5,          !- Blind Top Opening Multiplier
0.5,          !- Blind Bottom Opening Multiplier
0.0,          !- Blind Left Side Opening Multiplier
0.0,          !- Blind Right Side Opening Multiplier
0,           !- Minimum Slat Angle {deg}
180;         !- Maximum Slat Angle {deg}

```

!- ===== ALL OBJECTS IN CLASS: WINDOWPROPERTY:SHADINGCONTROL =====

```

WindowProperty:ShadingControl,
ALWAYS_ON,      !- Name
InteriorBlind,  !- Shading Type
CGP_Ext_Window1, !- Construction with Shading Name
AlwaysOn,       !- Shading Control Type
always_on,      !- Schedule Name
,              !- Setpoint {W/m2, W or deg C}
NO,            !- Shading Control Is Scheduled
NO,           !- Glare Control Is Active
,             !- Shading Device Material Name
FixedSlatAngle, !- Type of Slat Angle Control for Blinds
;            !- Slat Angle Schedule Name

```

```

WindowProperty:ShadingControl,
ALWAYS_OFF,     !- Name
InteriorBlind,  !- Shading Type
CGP_Ext_Window1, !- Construction with Shading Name
AlwaysOff,      !- Shading Control Type
,              !- Schedule Name
,             !- Setpoint {W/m2, W or deg C}
NO,            !- Shading Control Is Scheduled
NO,           !- Glare Control Is Active
,             !- Shading Device Material Name
FixedSlatAngle, !- Type of Slat Angle Control for Blinds
;            !- Slat Angle Schedule Name

```

```

WindowProperty:ShadingControl,
INCIDENT SOLAR ON BLIND, !- Name
InteriorBlind,  !- Shading Type
CGP_Ext_Window1, !- Construction with Shading Name
OnIfHighSolarOnWindow, !- Shading Control Type
,              !- Schedule Name
20,           !- Setpoint {W/m2, W or deg C}
NO,           !- Shading Control Is Scheduled

```

```

NO,          !- Glare Control Is Active
,           !- Shading Device Material Name
FixedSlatAngle, !- Type of Slat Angle Control for Blinds
;           !- Slat Angle Schedule Name

!- ===== ALL OBJECTS IN CLASS: OUTPUT:ENERGYMANAGEMENTSYSTEM =====

!WINDOW 3

EnergyManagementSystem:ProgramCallingManager,
  Window Shading Device EMS Controller2301, !- Name
  BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
  Set_Shade_Control_State2301; !- Program Name 1

EnergyManagementSystem:Actuator,
  Sub_Surface_zn_ne_04_e_Shading_Deploy_Status, !- Name
  zn_ne_04_e, !- Actuated Component Unique Name
  Window Shading Control, !- Actuated Component Type
  Control Status; !- Actuated Component Control Type

EnergyManagementSystem:Sensor,
  Solar_Horizontal_Profile_Angle_Cos2301, !- Name
  zn_ne_04_e, !- Output:Variable or Output:Meter Index Key Name
  Surface Window Solar Horizontal Profile Angle; !- Output:Variable or Output:Meter Name

EnergyManagementSystem:TrendVariable,
  SBIC2301, !- Name
  Solar_Horizontal_Profile_Angle_Cos2301, !- EMS Variable Name
  3; !- Number of Timesteps to be Logged

EnergyManagementSystem:TrendVariable,
  SPT2301, !- Name
  Shade_Position2301, !- EMS Variable Name
  3; !- Number of Timesteps to be Logged

EnergyManagementSystem:Sensor,
  Shade_Position2301, !- Name
  EMS, !- Output:Variable or Output:Meter Index Key Name
  Erl Shading Control Status2301; !- Output:Variable or Output:Meter Name

! !CONTROL ALGORITHMS
EnergyManagementSystem:Program,
  Set_Shade_Control_State2301, !- Name
  Set HorizontalProfileAngleRadians = @DegtoRad Solar_Horizontal_Profile_Angle_Cos2301,
  Set CosHPAR = @cos HorizontalProfileAngleRadians,
  Set SinHPAR = @sin HorizontalProfileAngleRadians,
  Set TanHPAR = SinHPAR / CosHPAR, !- <none>
  Set PD = 3.556 / TanHPAR, !- <none>
  Set MAX1to3 = @TrendMax SPT2301 3, !-Program Line 7
  Set DSR_MAX = @TrendMax DSR 3, !-Program Line 8
  Set SBIC_MIN = @TrendMin SBIC2301 3,
  Set SBIC_MAX = @TrendMax SBIC2301 3,
  Set SBIC_Pre = @TrendValue SBIC2301 3,
  Set SPT2401_Pre = @TrendValue SPT2401 1,
  Set SPT2301_Pre = @TrendValue SPT62301 1,
  Set DSR_Previous = @TrendValue DSR 1,
  Set HPA_Max = @TrendValue SBIC2301 3,
  IF Direct_Solar == 0 && SBIC2301 == 0 && MAX1to3 == 0,
  Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Off2301,
  ELSEIF PD > 0.5 && Direct_Solar >= 120, !- Program Line 10
  Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2301, !- Program Line 11
  ELSEIF Direct_Solar < 120 && SBIC_MIN < 81.996 && SBIC_MAX <> 0 && MAX1to3 > 0 && DSR_MAX > 120,
  Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2301,
  ELSEIF Direct_Solar >= 120 && SBIC_MIN < 81.996 && SBIC_MIN > 0 && MAX1to3 > 0,
  Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2301,
  ELSEIF Direct_Solar >= 120 && SBIC_Pre == 0 && SBIC_MAX < 81.996 && MAX1to3 > 0,
  Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2301,

```

```

ELSEIF Direct_Solar >= 120 && SBIC_MIN < 81.996 && MAX1to3 > 0 && SPT2401_Pre > 0, !- <none>
Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2301, !- <none>
ELSEIF Direct_Solar >= 120 && HPA_Max < 81.996 && HPA_Max > 25,
Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2301,
ELSE, !- Program Line 22
Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Off2301, !- Program Line 23
ENDIF;           !- Program Line 24

```

```

EnergyManagementSystem:OutputVariable,
Erl Shading Control Status2301, !- Name
Sub_Surface_zn_ne_04_e_Shading_Deploy_Status, !- EMS Variable Name
Averaged,           !- Type of Data in Variable
ZoneTimeStep;      !- Update Frequency

```

```

EnergyManagementSystem:ProgramCallingManager,
Init Window Shading Device Control Constants2301, !- Name
BeginNewEnvironment, !- EnergyPlus Model Calling Point
InitializeShadeControlFlags2301; !- Program Name 1

```

```

EnergyManagementSystem:Program,
InitializeShadeControlFlags2301, !- Name
Set Shade_Status_None2301 = 0.0 - 1.0, !- Program Line 1
Set Shade_Status_Off2301 = 0.0, !- Program Line 2
Set Shade_Status_Interior_Blind_On2301 = 6.0; !- <none>

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_None2301; !- Erl Variable 1 Name

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_Off2301; !- Erl Variable 1 Name

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_Interior_Blind_On2301; !- Erl Variable 1 Name

```

!WINDOW 4

```

EnergyManagementSystem:ProgramCallingManager,
Window Shading Device EMS Controller2401, !- Name
BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
Set_Shade_Control_State2401; !- Program Name 1

```

```

EnergyManagementSystem:Actuator,
Sub_Surface_zn_ne_01_e_Shading_Deploy_Status, !- Name
zn_ne_01_e, !- Actuated Component Unique Name
Window Shading Control, !- Actuated Component Type
Control Status; !- Actuated Component Control Type

```

```

EnergyManagementSystem:Sensor,
Solar_Horizontal_Profile_Angle_Cos2401, !- Name
zn_ne_01_e, !- Output:Variable or Output:Meter Index Key Name
Surface Window Solar Horizontal Profile Angle; !- Output:Variable or Output:Meter Name

```

```

EnergyManagementSystem:TrendVariable,
SBIC2401, !- Name
Solar_Horizontal_Profile_Angle_Cos2401, !- EMS Variable Name
3; !- Number of Timesteps to be Logged

```

```

EnergyManagementSystem:TrendVariable,
SPT2401, !- Name
Shade_Position2401, !- EMS Variable Name
3; !- Number of Timesteps to be Logged

```

```

EnergyManagementSystem:Sensor,
Shade_Position2401, !- Name
EMS, !- Output:Variable or Output:Meter Index Key Name

```

Erl Shading Control Status2401; !- Output:Variable or Output:Meter Name

```

EnergyManagementSystem:Program,
Set_Shade_Control_State2401, !- Name
Set HorizontalProfileAngleRadians = @DegtoRad Solar_Horizontal_Profile_Angle_Cos2401,
Set CosHPAR = @cos HorizontalProfileAngleRadians,
Set SinHPAR = @sin HorizontalProfileAngleRadians,
Set TanHPAR = SinHPAR / CosHPAR, !- <none>
Set PD = 3.556 / TanHPAR, !- <none>
Set MAX1to3 = @TrendMax SPT2401 3, !-Program Line 7
Set DSR_MAX = @TrendMax DSR 3, !-Program Line 8
Set DSR_MIN = @TrendMin DSR 3, !-Program Line 8
Set SBIC_MIN = @TrendMIN SBIC2401 3,
Set SBIC_MAX = @TrendMax SBIC2401 3,
Set SBIC_Pre = @TrendValue SBIC2401 3,
Set SPT2501_Pre = @TrendValue SPT2501 1,
Set SPT2401_Pre = @TrendValue SPT2401 1,
Set DSR_Previous = @TrendValue DSR 1,
Set HPA_Max = @TrendValue SBIC2401 3,
IF Direct_solar == 0 && SBIC2401 == 0 && MAX1to3 == 0,
Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Off2401,
ELSEIF PD > 1 && Direct_Solar >= 120, !- Program Line 10
Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2401, !- Program Line 11
ELSEIF Direct_Solar < 120 && SBIC_MIN < 74.293 && SBIC_MAX <> 0 && MAX1to3 > 0 && DSR_MAX > 120,
Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2401,
ELSEIF Direct_Solar >= 120 && SBIC_MIN < 74.293 && SBIC_MIN > 0 && MAX1to3 > 0,
Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2401,
ELSEIF Direct_Solar >= 120 && SBIC_Pre == 0 && SBIC_MAX < 74.293 && MAX1to3 > 0,
Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2401,
ELSEIF Direct_Solar >= 120 && SBIC_MIN < 74.293 && MAX1to3 > 0 && SPT2501_Pre > 0,
Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2401,
ELSEIF Direct_Solar >= 120 && HPA_Max < 74.293 && HPA_Max > 25,
Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2401,
ELSE, !- Program Line 22
Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Off2401, !- Program Line 23
ENDIF;        !- Program Line 24

```

```

EnergyManagementSystem:OutputVariable,
Erl Shading Control Status2401, !- Name
Sub_Surface_zn_ne_01_e_Shading_Deploy_Status, !- EMS Variable Name
Averaged,        !- Type of Data in Variable
ZoneTimeStep;        !- Update Frequency

```

```

EnergyManagementSystem:ProgramCallingManager,
Init Window Shading Device Control Constants2401, !- Name
BeginNewEnvironment,    !- EnergyPlus Model Calling Point
InitializeShadeControlFlags2401; !- Program Name 1

```

```

EnergyManagementSystem:Program,
InitializeShadeControlFlags2401, !- Name
Set Shade_Status_None2401 = 0.0 - 1.0, !- Program Line 1
Set Shade_Status_Off2401 = 0.0, !- Program Line 2
Set Shade_Status_Interior_Blind_On2401 = 6.0; !- <none>

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_None2401;    !- Erl Variable 1 Name

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_Off2401;    !- Erl Variable 1 Name

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_Interior_Blind_On2401; !- Erl Variable 1 Name

```

!WINDOW 5

```

EnergyManagementSystem:TrendVariable,
  SPT2501,          !- Name
  Shade_Position2501,    !- EMS Variable Name
  2;                !- Number of Timesteps to be Logged

```

```

EnergyManagementSystem:Sensor,
  Shade_Position2501,    !- Name
  EMS,                  !- Output:Variable or Output:Meter Index Key Name
  Erl Shading Control Status2501;    !- Output:Variable or Output:Meter Name

```

```

EnergyManagementSystem:ProgramCallingManager,
  Window Shading Device EMS Controller2501, !- Name
  BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
  Set_Shade_Control_State2501; !- Program Name 1

```

```

EnergyManagementSystem:Actuator,
  Sub_Surface_zn_ne_02_e_Shading_Deploy_Status, !- Name
  zn_ne_02_e, !- Actuated Component Unique Name
  Window Shading Control, !- Actuated Component Type
  Control Status; !- Actuated Component Control Type

```

```

EnergyManagementSystem:Sensor,
  Solar_Horizontal_Profile_Angle_Cos2501, !- Name
  zn_ne_02_e, !- Output:Variable or Output:Meter Index Key Name
  Surface Window Solar Horizontal Profile Angle; !- Output:Variable or Output:Meter Name

```

```

EnergyManagementSystem:TrendVariable,
  SBIC2501,          !- Name
  Solar_Horizontal_Profile_Angle_Cos2501,    !- EMS Variable Name
  2;                !- Number of Timesteps to be Logged

```

```

EnergyManagementSystem:Program,
  Set_Shade_Control_State2501, !- Name
  Set HorizontalProfileAngleRadians = @DegtoRad Solar_Horizontal_Profile_Angle_Cos2501,
  Set CosHPAR = @cos HorizontalProfileAngleRadians,
  Set SinHPAR = @sin HorizontalProfileAngleRadians,
  Set TanHPAR = SinHPAR / CosHPAR, !- <none>
  Set PD = 3.556 / TanHPAR, !- <none>
  Set MAX1to3 = @TrendMax SPT2501 2, !-Program Line 7
  Set DSR_MAX = @TrendMax DSR 2, !-Program Line 8
  Set SBIC_MIN = @TrendMIN SBIC2501 2,
  Set SBIC_MAX = @TrendMax SBIC2501 2,
  Set SPT2602_Pre = @TrendValue SPT2602 1,
  Set SPT2501_Pre = @TrendValue SPT2501 1,
  Set DSR_Previous = @TrendValue DSR 1,
  IF Direct_Solar == 0 && SBIC2501 == 0 && MAX1to3 == 0,
  Set Sub_Surface_zn_ne_02_e_Shading_Deploy_Status = Shade_Status_Off2501,
  ELSEIF PD > 1.5 && Direct_Solar >= 120, !- Program Line 10
  Set Sub_Surface_zn_ne_02_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2501, !- Program Line 11
  ELSEIF Direct_Solar < 120 && SBIC_MIN < 67.129 && MAX1to3 > 0 && DSR_MAX > 120,
  Set Sub_Surface_zn_ne_02_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2501,
  ELSEIF Direct_Solar >= 120 && SBIC_MIN < 67.129 && SBIC_MIN > 0 && MAX1to3 > 0,
  Set Sub_Surface_zn_ne_02_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2501,
  ELSEIF Direct_Solar >= 120 && SBIC_MIN < 67.129 && MAX1to3 > 0 && SPT2602_Pre > 0,
  Set Sub_Surface_zn_ne_02_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2501,
  ELSE, !- Program Line 22
  Set Sub_Surface_zn_ne_02_e_Shading_Deploy_Status = Shade_Status_Off2501, !- Program Line 23
  ENDIF;    !- Program Line 24

```

```

EnergyManagementSystem:OutputVariable,
  Erl Shading Control Status2501, !- Name
  Sub_Surface_zn_ne_02_e_Shading_Deploy_Status, !- EMS Variable Name
  Averaged, !- Type of Data in Variable
  ZoneTimeStep; !- Update Frequency

```

```

EnergyManagementSystem:ProgramCallingManager,
  Init Window Shading Device Control Constants2501, !- Name
  BeginNewEnvironment, !- EnergyPlus Model Calling Point
  InitializeShadeControlFlags2501; !- Program Name 1

```

```

EnergyManagementSystem:Program,
  InitializeShadeControlFlags2501, !- Name
  Set Shade_Status_None2501 = 0.0 - 1.0, !- Program Line 1
  Set Shade_Status_Off2501 = 0.0, !- Program Line 2
  Set Shade_Status_Interior_Blind_On2501 = 6.0; !- <none>

```

```

EnergyManagementSystem:GlobalVariable,
  Shade_Status_None2501; !- Erl Variable 1 Name

```

```

EnergyManagementSystem:GlobalVariable,
  Shade_Status_Off2501; !- Erl Variable 1 Name

```

```

EnergyManagementSystem:GlobalVariable,
  Shade_Status_Interior_Blind_On2501; !- Erl Variable 1 Name

```

```
!WINDOW 6
```

```

EnergyManagementSystem:TrendVariable,
  SPT2601, !- Name
  Shade_Position2601, !- EMS Variable Name
  2; !- Number of Timesteps to be Logged

```

```

EnergyManagementSystem:Sensor,
  Shade_Position2601, !- Name
  EMS, !- Output:Variable or Output:Meter Index Key Name
  Erl Shading Control Status2601; !- Output:Variable or Output:Meter Name

```

```

EnergyManagementSystem:ProgramCallingManager,
  Window Shading Device EMS Controller2601, !- Name
  BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
  Set_Shade_Control_State2601; !- Program Name 1

```

```

EnergyManagementSystem:Actuator,
  Sub_Surface_zn_ne_02_w_Shading_Deploy_Status, !- Name
  zn_ne_02_w, !- Actuated Component Unique Name
  Window Shading Control, !- Actuated Component Type
  Control Status; !- Actuated Component Control Type

```

```

EnergyManagementSystem:Sensor,
  Solar_Horizontal_Profile_Angle_Cos2601, !- Name
  zn_ne_02_w, !- Output:Variable or Output:Meter Index Key Name
  Surface Window Solar Horizontal Profile Angle; !- Output:Variable or Output:Meter Name

```

```

EnergyManagementSystem:TrendVariable,
  SBIC2601, !- Name
  Solar_Horizontal_Profile_Angle_Cos2601, !- EMS Variable Name
  2; !- Number of Timesteps to be Logged

```

```

EnergyManagementSystem:Program,
  Set_Shade_Control_State2601, !- Name
  Set HorizontalProfileAngleRadians = @DegtoRad Solar_Horizontal_Profile_Angle_Cos2601,
  Set CosHPAR = @cos HorizontalProfileAngleRadians,
  Set SinHPAR = @sin HorizontalProfileAngleRadians,
  Set TanHPAR = SinHPAR / CosHPAR, !- <none>
  Set PD = 3.556 / TanHPAR, !- <none>
  Set MAX1to3 = @TrendMax SPT2601 2, !-Program Line 7
  Set DSR_MAX = @TrendMax DSR 2, !-Program Line 8
  Set SBIC_MIN = @TrendMIN SBIC2601 2,
  Set SBIC_MAX = @TrendMax SBIC2601 2,
  Set SPT2802_Pre = @TrendValue SPT2802 1,
  Set SPT2601_Pre = @TrendValue SPT2601 1,
  Set DSR_Previous = @TrendValue DSR 1,
  IF Direct_Solar >= 0 && SBIC2601 == 0 && MAX1to3 == 0,
  Set Sub_Surface_zn_ne_02_w_Shading_Deploy_Status = Shade_Status_Off2601,
  ELSEIF PD > 2 && Direct_Solar >= 120, !- Program Line 10

```

```

Set Sub_Surface_zn_ne_02_w_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2601, !- Program Line 11
ELSEIF Direct_Solar < 120 && SBIC_MIN < 60.645 && MAX1to3 > 0 && DSR_MAX > 120,
Set Sub_Surface_zn_ne_02_w_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2601,
ELSEIF Direct_Solar >= 120 && SBIC_MIN < 60.645 && SBIC_MIN > 0 && MAX1to3 > 0,
Set Sub_Surface_zn_ne_02_w_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2601,
ELSEIF Direct_Solar >= 120 && SBIC_MIN < 60.645 && SPT2802_Pre > 0 && MAX1to3 > 0,
Set Sub_Surface_zn_ne_02_w_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2601,
ELSE, !- Program Line 22
Set Sub_Surface_zn_ne_02_w_Shading_Deploy_Status = Shade_Status_Off2601, !- Program Line 23
ENDIF;      !- Program Line 24

```

```

EnergyManagementSystem:OutputVariable,
Erl Shading Control Status2601, !- Name
Sub_Surface_zn_ne_02_w_Shading_Deploy_Status, !- EMS Variable Name
Averaged,      !- Type of Data in Variable
ZoneTimeStep;  !- Update Frequency

```

```

EnergyManagementSystem:ProgramCallingManager,
Init Window Shading Device Control Constants2601, !- Name
BeginNewEnvironment,  !- EnergyPlus Model Calling Point
InitializeShadeControlFlags2601; !- Program Name 1

```

```

EnergyManagementSystem:Program,
InitializeShadeControlFlags2601, !- Name
Set Shade_Status_None2601 = 0.0 - 1.0, !- Program Line 1
Set Shade_Status_Off2601 = 0.0, !- Program Line 2
Set Shade_Status_Interior_Blind_On2601 = 6.0; !- <none>

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_None2601; !- Erl Variable 1 Name

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_Off2601;  !- Erl Variable 1 Name

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_Interior_Blind_On2601; !- Erl Variable 1 Name

```

!!WINDOW 7

```

EnergyManagementSystem:TrendVariable,
SPT2701,      !- Name
Shade_Position2701,      !- EMS Variable Name
1;           !- Number of Timesteps to be Logged

```

```

EnergyManagementSystem:Sensor,
Shade_Position2701,      !- Name
EMS,                    !- Output:Variable or Output:Meter Index Key Name
Erl Shading Control Status2701;      !- Output:Variable or Output:Meter Name

```

```

EnergyManagementSystem:ProgramCallingManager,
Window Shading Device EMS Controller2701, !- Name
BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
Set_Shade_Control_State2701; !- Program Name 1

```

```

EnergyManagementSystem:Actuator,
Sub_Surface_zn_ne_07_n_Shading_Deploy_Status, !- Name
zn_ne_07_n, !- Actuated Component Unique Name
Window Shading Control, !- Actuated Component Type
Control Status;      !- Actuated Component Control Type

```

```

EnergyManagementSystem:Sensor,
Solar_Horizontal_Profile_Angle_Cos2701, !- Name
zn_ne_07_n, !- Output:Variable or Output:Meter Index Key Name

```

Surface Window Solar Horizontal Profile Angle; !- Output:Variable or Output:Meter Name

```

EnergyManagementSystem:TrendVariable,
SBIC2701,          !- Name
Solar_Horizontal_Profile_Angle_Cos2701,          !- EMS Variable Name
1;                !- Number of Timesteps to be Logged

EnergyManagementSystem:Program,
Set_Shade_Control_State2701, !- Name
Set HorizontalProfileAngleRadians = @DegtoRad Solar_Horizontal_Profile_Angle_Cos2701,
Set CosHPAR = @cos HorizontalProfileAngleRadians,
Set SinHPAR = @sin HorizontalProfileAngleRadians,
Set TanHPAR = SinHPAR / CosHPAR, !- <none>
Set PD = 3.556 / TanHPAR, !- <none>
Set MAX1to3 = @TrendMax SPT2701 1, !-Program Line 7
Set DSR_MAX = @TrendMax DSR 1, !-Program Line 8
Set SBIC_MIN = @TrendMIN SBIC2701 1,
Set SPT2801_Pre = @TrendValue SPT2801 1,
Set SPT2701_Pre = @TrendValue SPT2701 1,
Set DSR_Previous = @TrendValue DSR 1,
IF PD > 2.5 && Direct_Solar >= 120, !- Program Line 10
Set Sub_Surface_zn_ne_07_n_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2701, !- Program Line 11
ELSEIF Direct_Solar < 120 && SBIC_MIN < 54.891 && MAX1to3 > 0 && DSR_MAX > 120,
Set Sub_Surface_zn_ne_07_n_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2701,
ELSEIF Direct_Solar >= 120 && SBIC_MIN < 54.891 && SBIC_MIN > 0 && MAX1to3 > 0,
Set Sub_Surface_zn_ne_07_n_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2701,
ELSEIF Direct_Solar >= 120 && SBIC_MIN < 54.891 && SPT2801_Pre > 0 && MAX1to3 > 0,
Set Sub_Surface_zn_ne_07_n_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2701,
ELSE, !- Program Line 22
Set Sub_Surface_zn_ne_07_n_Shading_Deploy_Status = Shade_Status_Off2701, !- Program Line 23
ENDIF;          !- Program Line 24

```

```

EnergyManagementSystem:OutputVariable,
Erl Shading Control Status2701, !- Name
Sub_Surface_zn_ne_07_n_Shading_Deploy_Status, !- EMS Variable Name
Averaged,          !- Type of Data in Variable
ZoneTimeStep;     !- Update Frequency

```

```

EnergyManagementSystem:ProgramCallingManager,
Init Window Shading Device Control Constants2701, !- Name
BeginNewEnvironment, !- EnergyPlus Model Calling Point
InitializeShadeControlFlags2701; !- Program Name 1

```

```

EnergyManagementSystem:Program,
InitializeShadeControlFlags2701, !- Name
Set Shade_Status_None2701 = 0.0 - 1.0, !- Program Line 1
Set Shade_Status_Off2701 = 0.0, !- Program Line 2
Set Shade_Status_Interior_Blind_On2701 = 6.0; !- <none>

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_None2701; !- Erl Variable 1 Name

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_Off2701; !- Erl Variable 1 Name

```

```

EnergyManagementSystem:GlobalVariable,
Shade_Status_Interior_Blind_On2701; !- Erl Variable 1 Name

```

!WINDOW 8

```

EnergyManagementSystem:TrendVariable,
SPT2801,          !- Name
Shade_Position2801,          !- EMS Variable Name
1;                !- Number of Timesteps to be Logged

```

```

EnergyManagementSystem:Sensor,
Shade_Position2801,          !- Name

```


EMS, !- Output:Variable or Output:Meter Index Key Name
 Erl Shading Control Status2801; !- Output:Variable or Output:Meter Name

EnergyManagementSystem:ProgramCallingManager,
 Window Shading Device EMS Controller2801, !- Name
 BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
 Set_Shade_Control_State2801; !- Program Name 1

EnergyManagementSystem:Actuator,
 Sub_Surface_zn_ne_09_n_Shading_Deploy_Status, !- Name
 zn_ne_09_n, !- Actuated Component Unique Name
 Window Shading Control, !- Actuated Component Type
 Control Status; !- Actuated Component Control Type

EnergyManagementSystem:Sensor,
 Solar_Horizontal_Profile_Angle_Cos2801, !- Name
 zn_ne_09_n, !- Output:Variable or Output:Meter Index Key Name
 Surface Window Solar Horizontal Profile Angle; !- Output:Variable or Output:Meter Name

EnergyManagementSystem:TrendVariable,
 SBIC2801, !- Name
 Solar_Horizontal_Profile_Angle_Cos2801, !- EMS Variable Name
 1; !- Number of Timesteps to be Logged

EnergyManagementSystem:Program,
 Set_Shade_Control_State2801, !- Name
 Set HorizontalProfileAngleRadians = @DegtoRad Solar_Horizontal_Profile_Angle_Cos2801,
 Set CosHPAR = @cos HorizontalProfileAngleRadians,
 Set SinHPAR = @sin HorizontalProfileAngleRadians,
 Set TanHPAR = SinHPAR / CosHPAR, !- <none>
 Set PD = 3.556 / TanHPAR, !- <none>
 Set MAX1to3 = @TrendMax SPT2801 1, !-Program Line 7
 Set DSR_MAX = @TrendMax DSR 1, !-Program Line 8
 Set SBIC_MIN = @TrendMIN SBIC2801 1,
 IF PD > 3 && Direct_Solar >= 120, !- Program Line 10
 Set Sub_Surface_zn_ne_09_n_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2801, !- Program Line 2801
 ELSEIF Direct_Solar < 120 && SBIC_MIN < 49.848 && MAX1to3 > 0 && DSR_MAX > 120,
 Set Sub_Surface_zn_ne_09_n_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2801,
 ELSEIF Direct_Solar >= 120 && SBIC_MIN < 49.848 && SBIC_MIN > 0 && MAX1to3 > 0,
 Set Sub_Surface_zn_ne_09_n_Shading_Deploy_Status = Shade_Status_Interior_Blind_On2801,
 ELSE, !- Program Line 22
 Set Sub_Surface_zn_ne_09_n_Shading_Deploy_Status = Shade_Status_Off2801, !- Program Line 23
 ENDIF; !- Program Line 24

EnergyManagementSystem:OutputVariable,
 Erl Shading Control Status2801, !- Name
 Sub_Surface_zn_ne_09_n_Shading_Deploy_Status, !- EMS Variable Name
 Averaged, !- Type of Data in Variable
 ZoneTimeStep; !- Update Frequency

EnergyManagementSystem:ProgramCallingManager,
 Init Window Shading Device Control Constants2801, !- Name
 BeginNewEnvironment, !- EnergyPlus Model Calling Point
 InitializeShadeControlFlags2801; !- Program Name 1

EnergyManagementSystem:Program,
 InitializeShadeControlFlags2801, !- Name
 Set Shade_Status_None2801 = 0.0 - 1.0, !- Program Line 1
 Set Shade_Status_Off2801 = 0.0, !- Program Line 2
 Set Shade_Status_Interior_Blind_On2801 = 6.0; !- <none>

EnergyManagementSystem:GlobalVariable,
 Shade_Status_None2801; !- Erl Variable 1 Name

EnergyManagementSystem:GlobalVariable,
 Shade_Status_Off2801; !- Erl Variable 1 Name

EnergyManagementSystem:GlobalVariable,
Shade_Status_Interior_Blind_On2801; !- Erl Variable 1 Name

!- ===== ALL OBJECTS IN CLASS: OUTPUT:VARIABLE =====

Output:Variable,*,Erl Shading Control Status2301,Timestep;
Output:Variable,*,Erl Shading Control Status2401,Timestep;
Output:Variable,*,Erl Shading Control Status2501,Timestep;
Output:Variable,*,Erl Shading Control Status2601,Timestep;
Output:Variable,*,Erl Shading Control Status2701,Timestep;
Output:Variable,*,Erl Shading Control Status2801,Timestep;

APPENDIX G: BLINDSWITCH-2012B SAMPLE INPUT FILE

Similar to Blindswitch-A, 10 adjacent windows as a group were shown below on the north-east façade. The same window geometry, material, construction, amount of operable windows, window shade material, and shading control objects as with Blindswitch-2012A is applied here. Blindswitch-2012B algorithm was represented by EnergyManagementSystem:Program object. The code seen here is identical for each façade and floor, but uses different exterior vertical illuminance values. An external CSV file is read, using the Schedule:File object, which contains the vertical exterior illuminance values gathered from the daylighting engine RADIANCE.

```
!- ===== ALL OBJECTS IN CLASS: CONSTRUCTION =====
```

```
Construction,
  CGP_Ext_Window1,    !- Name
  Clear 3mm,          !- Outside Layer
  000_Air 13mm,       !- Layer 2
  Clear 3mm,          !- Layer 3
  BLIND;              !- Layer 4
```

```
!- ===== ALL OBJECTS IN CLASS: WINDOWMATERIAL:BLIND =====
```

```
WindowMaterial:Blind,
  BLIND,              !- Name
  HORIZONTAL,         !- Slat Orientation
  0.0508,             !- Slat Width {m}
  0.0508,             !- Slat Separation {m}
  0.001,              !- Slat Thickness {m}
  15,                 !- Slat Angle {deg}
  0.1,                !- Slat Conductivity {W/m-K}
  0.0,                !- Slat Beam Solar Transmittance
  0.7,                !- Front Side Slat Beam Solar Reflectance
  0.7,                !- Back Side Slat Beam Solar Reflectance
  0.0,                !- Slat Diffuse Solar Transmittance
  0.7,                !- Front Side Slat Diffuse Solar Reflectance
  0.7,                !- Back Side Slat Diffuse Solar Reflectance
  0.0,                !- Slat Beam Visible Transmittance
  0.5,                !- Front Side Slat Beam Visible Reflectance
  0.5,                !- Back Side Slat Beam Visible Reflectance
  0.0,                !- Slat Diffuse Visible Transmittance
  0.5,                !- Front Side Slat Diffuse Visible Reflectance
  0.5,                !- Back Side Slat Diffuse Visible Reflectance
  0.0,                !- Slat Infrared Hemispherical Transmittance
  0.9,                !- Front Side Slat Infrared Hemispherical Emissivity
  0.9,                !- Back Side Slat Infrared Hemispherical Emissivity
  0.050,              !- Blind to Glass Distance {m}
  0.5,                !- Blind Top Opening Multiplier
  0.5,                !- Blind Bottom Opening Multiplier
```

```

0.0,      !- Blind Left Side Opening Multiplier
0.0,      !- Blind Right Side Opening Multiplier
0,        !- Minimum Slat Angle {deg}
180;     !- Maximum Slat Angle {deg}

```

```
!- ===== ALL OBJECTS IN CLASS: WINDOWPROPERTY:SHADINGCONTROL =====
```

```

WindowProperty:ShadingControl,
  ALWAYS_ON,      !- Name
  InteriorBlind,  !- Shading Type
  CGP_Ext_Window1, !- Construction with Shading Name
  AlwaysOn,       !- Shading Control Type
  always_on,     !- Schedule Name
  ,              !- Setpoint {W/m2, W or deg C}
  NO,            !- Shading Control Is Scheduled
  NO,            !- Glare Control Is Active
  ,              !- Shading Device Material Name
  FixedSlatAngle, !- Type of Slat Angle Control for Blinds
  ;              !- Slat Angle Schedule Name

```

```

WindowProperty:ShadingControl,
  ALWAYS_OFF,     !- Name
  InteriorBlind,  !- Shading Type
  CGP_Ext_Window1, !- Construction with Shading Name
  AlwaysOff,      !- Shading Control Type
  ,              !- Schedule Name
  ,              !- Setpoint {W/m2, W or deg C}
  NO,            !- Shading Control Is Scheduled
  NO,            !- Glare Control Is Active
  ,              !- Shading Device Material Name
  FixedSlatAngle, !- Type of Slat Angle Control for Blinds
  ;              !- Slat Angle Schedule Name

```

```

WindowProperty:ShadingControl,
  INCIDENT SOLAR ON BLIND, !- Name
  InteriorBlind,          !- Shading Type
  CGP_Ext_Window1,       !- Construction with Shading Name
  OnIfHighSolarOnWindow, !- Shading Control Type
  ,                      !- Schedule Name
  20,                   !- Setpoint {W/m2, W or deg C}
  NO,                   !- Shading Control Is Scheduled
  NO,                   !- Glare Control Is Active
  ,                      !- Shading Device Material Name
  FixedSlatAngle,       !- Type of Slat Angle Control for Blinds
  ;                      !- Slat Angle Schedule Name

```

```
!- ===== ALL OBJECTS IN CLASS: SCHEDULE:FILE =====
```

```

Schedule:File,
  File6,                !- Name
  Any Number,           !- ScheduleType
  simplot_sensors.csv,  !- Name of File
  9,                   !- Column Number
  1,                   !- Rows to Skip at Top
  8760,                !- Number of Hours of Data
  Comma;               !- Column Separator

```

```

EnergyManagementSystem:Sensor,
  Sensor6,             !- Name
  File6,               !- Output:Variable or Output:Meter Index Key Name
  Schedule Value;     !- Output:Variable or Output:Meter Name

```

```

Schedule:File,
  File8,                !- Name
  Any Number,           !- ScheduleType
  simplot_sensors.csv, !- Name of File
  11,                   !- Column Number
  1,                     !- Rows to Skip at Top
  8760,                 !- Number of Hours of Data
  Comma;                !- Column Separator

```

```

EnergyManagementSystem:Sensor,
  Sensor8,              !- Name
  File8,                !- Output:Variable or Output:Meter Index Key Name
  Schedule Value;      !- Output:Variable or Output:Meter Name

```

```

Schedule:File,
  File9,                !- Name
  Any Number,           !- ScheduleType
  simplot_sensors.csv, !- Name of File
  12,                   !- Column Number
  1,                     !- Rows to Skip at Top
  8760,                 !- Number of Hours of Data
  Comma;                !- Column Separator

```

```

EnergyManagementSystem:Sensor,
  Sensor9,              !- Name
  File9,                !- Output:Variable or Output:Meter Index Key Name
  Schedule Value;      !- Output:Variable or Output:Meter Name

```

```

Schedule:File,
  File10,               !- Name
  Any Number,           !- ScheduleType
  simplot_sensors.csv, !- Name of File
  13,                   !- Column Number
  1,                     !- Rows to Skip at Top
  8760,                 !- Number of Hours of Data
  Comma;                !- Column Separator

```

```

EnergyManagementSystem:Sensor,
  Sensor10,             !- Name
  File10,               !- Output:Variable or Output:Meter Index Key Name
  Schedule Value;      !- Output:Variable or Output:Meter Name

```

```

Schedule:File,
  File12,               !- Name
  Any Number,           !- ScheduleType
  simplot_sensors.csv, !- Name of File
  15,                   !- Column Number
  1,                     !- Rows to Skip at Top
  8760,                 !- Number of Hours of Data
  Comma;                !- Column Separator

```

```

EnergyManagementSystem:Sensor,
  Sensor12,             !- Name
  File12,               !- Output:Variable or Output:Meter Index Key Name
  Schedule Value;      !- Output:Variable or Output:Meter Name

```

!- ===== ALL OBJECTS IN CLASS: OUTPUT:ENERGYMANAGEMENTSYSTEM =====

!WINDOW 3

EnergyManagementSystem:ProgramCallingManager,
 Window Shading Device EMS Controller2301, !- Name
 BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
 Set_Shade_Control_State2301; !- Program Name 1

EnergyManagementSystem:Actuator,
 Sub_Surface_zn_ne_04_e_Shading_Deploy_Status, !- Name
 zn_ne_04_e, !- Actuated Component Unique Name
 Window Shading Control, !- Actuated Component Type
 Control Status; !- Actuated Component Control Type

EnergyManagementSystem:TrendVariable,
 SPT2301, !- Name
 Shade_Position2301, !- EMS Variable Name
 1; !- Number of Timesteps to be Logged

EnergyManagementSystem:Sensor,
 Shade_Position2301, !- Name
 EMS, !- Output:Variable or Output:Meter Index Key Name
 Erl Shading Control Status2301; !- Output:Variable or Output:Meter Name

! CONTROL ALGORITHMS

EnergyManagementSystem:Program,
 Set_Shade_Control_State2301, !- Name
 Set SPT_Value = @TrendValue SPT2301 1, !- Program Line 1
 IF Sensor12 > 33000, !- Program Line 2
 Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A4
 ELSEIF Sensor12 < 17500 && SPT_Value > 0, !- A5
 Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Off, !- A6
 ELSEIF Sensor12 > 17500 && Sensor12 < 33000 && SPT_Value > 0, !- A7
 Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A8
 ELSE, !- A9
 Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Off, !- A10
 ENDIF; !- A11

EnergyManagementSystem:OutputVariable,
 Erl Shading Control Status2301, !- Name
 Sub_Surface_zn_ne_04_e_Shading_Deploy_Status, !- EMS Variable Name
 Averaged, !- Type of Data in Variable
 ZoneTimeStep; !- Update Frequency

EnergyManagementSystem:ProgramCallingManager,
 Init Window Shading Device Control Constants2301, !- Name
 BeginNewEnvironment, !- EnergyPlus Model Calling Point
 InitializeShadeControlFlags2301; !- Program Name 1

EnergyManagementSystem:Program,
 InitializeShadeControlFlags2301, !- Name
 Set Shade_Status_None = 0.0 - 1.0, !- Program Line 1
 Set Shade_Status_Off = 0.0, !- Program Line 2
 Set Shade_Status_Interior_Blind_On = 6.0; !- <none>

EnergyManagementSystem:GlobalVariable,
 Shade_Status_None; !- Erl Variable 1 Name

EnergyManagementSystem:GlobalVariable,
 Shade_Status_Off; !- Erl Variable 1 Name

EnergyManagementSystem:GlobalVariable,
 Shade_Status_Interior_Blind_On; !- Erl Variable 1 Name

!WINDOW 4

```
EnergyManagementSystem:ProgramCallingManager,
  Window Shading Device EMS Controller2401, !- Name
  BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
  Set_Shade_Control_State2401; !- Program Name 1
```

```
EnergyManagementSystem:Actuator,
  Sub_Surface_zn_ne_01_e_Shading_Deploy_Status, !- Name
  zn_ne_01_e, !- Actuated Component Unique Name
  Window Shading Control, !- Actuated Component Type
  Control Status; !- Actuated Component Control Type
```

```
EnergyManagementSystem:TrendVariable,
  SPT2401, !- Name
  Shade_Position2401, !- EMS Variable Name
  1; !- Number of Timesteps to be Logged
```

```
EnergyManagementSystem:Sensor,
  Shade_Position2401, !- Name
  EMS, !- Output:Variable or Output:Meter Index Key Name
  Erl Shading Control Status2401; !- Output:Variable or Output:Meter Name
```

! CONTROL ALGORITHMS

```
EnergyManagementSystem:Program,
  Set_Shade_Control_State2401, !- Name
  Set SPT_Value = @TrendValue SPT2401 1, !- Program Line 1
  IF Sensor6 > 47500, !- Program Line 2
  Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A4
  ELSEIF Sensor6 < 22500 && SPT_Value > 0, !- A5
  Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Off, !- A6
  ELSEIF Sensor6 > 22500 && Sensor6 < 47500 && SPT_Value > 0, !- A7
  Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A8
  ELSE, !- A9
  Set Sub_Surface_zn_ne_01_e_Shading_Deploy_Status = Shade_Status_Off, !- A10
  ENDIF; !- A11
```

```
EnergyManagementSystem:OutputVariable,
  Erl Shading Control Status2401, !- Name
  Sub_Surface_zn_ne_01_e_Shading_Deploy_Status, !- EMS Variable Name
  Averaged, !- Type of Data in Variable
  ZoneTimeStep; !- Update Frequency
```

```
EnergyManagementSystem:ProgramCallingManager,
  Init Window Shading Device Control Constants2401, !- Name
  BeginNewEnvironment, !- EnergyPlus Model Calling Point
  InitializeShadeControlFlags2401; !- Program Name 1
```

```
EnergyManagementSystem:Program,
  InitializeShadeControlFlags2401, !- Name
  Set Shade_Status_None = 0.0 - 1.0, !- Program Line 1
  Set Shade_Status_Off = 0.0, !- Program Line 2
  Set Shade_Status_Interior_Blind_On = 6.0; !- <none>
```

!WINDOW 5

```
EnergyManagementSystem:TrendVariable,
  SPT2501, !- Name
  Shade_Position2501, !- EMS Variable Name
  1; !- Number of Timesteps to be Logged
```

```
EnergyManagementSystem:Sensor,
  Shade_Position2501, !- Name
  EMS, !- Output:Variable or Output:Meter Index Key Name
  Erl Shading Control Status2501; !- Output:Variable or Output:Meter Name
```

```

EnergyManagementSystem:ProgramCallingManager,
Window Shading Device EMS Controller2501, !- Name
BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
Set_Shade_Control_State2501; !- Program Name 1

```

```

EnergyManagementSystem:Actuator,
Sub_Surface_zn_ne_02_e_Shading_Deploy_Status, !- Name
zn_ne_02_e, !- Actuated Component Unique Name
Window Shading Control, !- Actuated Component Type
Control Status; !- Actuated Component Control Type

```

! CONTROL ALGORITHMS

```

EnergyManagementSystem:Program,
Set_Shade_Control_State2501, !- Name
Set SPT_Value = @TrendValue SPT2501 1, !- Program Line 1
IF Sensor9 > 60000, !- Program Line 2
Set Sub_Surface_zn_ne_02_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A4
ELSEIF Sensor9 < 30000 && SPT_Value > 0, !- A5
Set Sub_Surface_zn_ne_02_e_Shading_Deploy_Status = Shade_Status_Off, !- A6
ELSEIF Sensor9 > 30000 && Sensor9 < 60000 && SPT_Value > 0, !- A7
Set Sub_Surface_zn_ne_02_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A8
ELSE, !- A9
Set Sub_Surface_zn_ne_02_e_Shading_Deploy_Status = Shade_Status_Off, !- A10
ENDIF; !- A11

```

```

EnergyManagementSystem:OutputVariable,
Erl Shading Control Status2501, !- Name
Sub_Surface_zn_ne_02_e_Shading_Deploy_Status, !- EMS Variable Name
Averaged, !- Type of Data in Variable
ZoneTimeStep; !- Update Frequency

```

```

EnergyManagementSystem:ProgramCallingManager,
Init Window Shading Device Control Constants2501, !- Name
BeginNewEnvironment, !- EnergyPlus Model Calling Point
InitializeShadeControlFlags2501; !- Program Name 1

```

```

EnergyManagementSystem:Program,
InitializeShadeControlFlags2501, !- Name
Set Shade_Status_None = 0.0 - 1.0, !- Program Line 1
Set Shade_Status_Off = 0.0, !- Program Line 2
Set Shade_Status_Interior_Blind_On = 6.0; !- <none>

```

!WINDOW 6

```

EnergyManagementSystem:TrendVariable,
SPT2601, !- Name
Shade_Position2601, !- EMS Variable Name
1; !- Number of Timesteps to be Logged

```

```

EnergyManagementSystem:Sensor,
Shade_Position2601, !- Name
EMS, !- Output:Variable or Output:Meter Index Key Name
Erl Shading Control Status2601; !- Output:Variable or Output:Meter Name

```

```

EnergyManagementSystem:ProgramCallingManager,
Window Shading Device EMS Controller2601, !- Name
BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
Set_Shade_Control_State2601; !- Program Name 1

```

```

EnergyManagementSystem:Actuator,
Sub_Surface_zn_ne_02_w_Shading_Deploy_Status, !- Name
zn_ne_02_w, !- Actuated Component Unique Name
Window Shading Control, !- Actuated Component Type
Control Status; !- Actuated Component Control Type

```

! CONTROL ALGORITHMS


```

EnergyManagementSystem:Program,
  Set_Shade_Control_State2601, !- Name
  Set SPT_Value = @TrendValue SPT2601 1, !- Program Line 1
  IF Sensor10 > 72500, !- Program Line 2
  Set Sub_Surface_zn_ne_02_w_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A4
  ELSEIF Sensor10 < 37500 && SPT_Value > 0, !- A5
  Set Sub_Surface_zn_ne_02_w_Shading_Deploy_Status = Shade_Status_Off, !- A6
  ELSEIF Sensor10 > 37500 && Sensor10 < 72500 && SPT_Value > 0, !- A7
  Set Sub_Surface_zn_ne_02_w_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A8
  ELSE, !- A9
  Set Sub_Surface_zn_ne_02_w_Shading_Deploy_Status = Shade_Status_Off, !- A10
  ENDIF; !- A11

```

```

EnergyManagementSystem:OutputVariable,
  Erl Shading Control Status2601, !- Name
  Sub_Surface_zn_ne_02_w_Shading_Deploy_Status, !- EMS Variable Name
  Averaged, !- Type of Data in Variable
  ZoneTimeStep; !- Update Frequency

```

```

EnergyManagementSystem:ProgramCallingManager,
  Init Window Shading Device Control Constants2601, !- Name
  BeginNewEnvironment, !- EnergyPlus Model Calling Point
  InitializeShadeControlFlags2601; !- Program Name 1

```

```

EnergyManagementSystem:Program,
  InitializeShadeControlFlags2601, !- Name
  Set Shade_Status_None = 0.0 - 1.0, !- Program Line 1
  Set Shade_Status_Off = 0.0, !- Program Line 2
  Set Shade_Status_Interior_Blind_On = 6.0; !- <none>

```

!!WINDOW 7

```

EnergyManagementSystem:TrendVariable,
  SPT2701, !- Name
  Shade_Position2701, !- EMS Variable Name
  1; !- Number of Timesteps to be Logged

```

```

EnergyManagementSystem:Sensor,
  Shade_Position2701, !- Name
  EMS, !- Output:Variable or Output:Meter Index Key Name
  Erl Shading Control Status2701; !- Output:Variable or Output:Meter Name

```

```

EnergyManagementSystem:ProgramCallingManager,
  Window Shading Device EMS Controller2701, !- Name
  BeginTimeStepBeforePredictor, !- EnergyPlus Model Calling Point
  Set_Shade_Control_State2701; !- Program Name 1

```

```

EnergyManagementSystem:Actuator,
  Sub_Surface_zn_ne_07_n_Shading_Deploy_Status, !- Name
  zn_ne_07_n, !- Actuated Component Unique Name
  Window Shading Control, !- Actuated Component Type
  Control Status; !- Actuated Component Control Type

```

! CONTROL ALGORITHMS

```

EnergyManagementSystem:Program,
  Set_Shade_Control_State2701, !- Name
  Set SPT_Value = @TrendValue SPT2701 1, !- Program Line 1
  IF Sensor8 > 86000, !- Program Line 2
  Set Sub_Surface_zn_ne_07_n_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A4
  ELSEIF Sensor8 < 42500 && SPT_Value > 0, !- A5
  Set Sub_Surface_zn_ne_07_n_Shading_Deploy_Status = Shade_Status_Off, !- A6
  ELSEIF Sensor8 > 42500 && Sensor8 < 86000 && SPT_Value > 0, !- A7
  Set Sub_Surface_zn_ne_07_n_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A8
  ELSE, !- A9
  Set Sub_Surface_zn_ne_07_n_Shading_Deploy_Status = Shade_Status_Off, !- A10
  ENDIF; !- A11

```

```

EnergyManagementSystem:OutputVariable,
  Erl_Shading_Control_Status2701, !- Name
  Sub_Surface_zn_ne_07_n_Shading_Deploy_Status, !- EMS Variable Name
  Averaged, !- Type of Data in Variable
  ZoneTimeStep; !- Update Frequency

```

```

EnergyManagementSystem:ProgramCallingManager,
  Init_Window_Shading_Device_Control_Constants2701, !- Name
  BeginNewEnvironment, !- EnergyPlus Model Calling Point
  InitializeShadeControlFlags2701; !- Program Name 1

```

```

EnergyManagementSystem:Program,
  InitializeShadeControlFlags2701, !- Name
  Set Shade_Status_None = 0.0 - 1.0, !- Program Line 1
  Set Shade_Status_Off = 0.0, !- Program Line 2
  Set Shade_Status_Interior_Blind_On = 6.0; !- <none>

```

!WINDOW 8

```

EnergyManagementSystem:TrendVariable,
  SPT2801, !- Name
  Shade_Position2801, !- EMS Variable Name
  1; !- Number of Timesteps to be Logged

```

```

EnergyManagementSystem:Sensor,
  Shade_Position2801, !- Name
  EMS, !- Output:Variable or Output:Meter Index Key Name
  Erl_Shading_Control_Status2801; !- Output:Variable or Output:Meter Name

```

```

EnergyManagementSystem:ProgramCallingManager,
  Window_Shading_Device_EMS_Controller2801, !- Name
  BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
  Set_Shade_Control_State2801; !- Program Name 1

```

```

EnergyManagementSystem:Actuator,
  Sub_Surface_zn_ne_09_n_Shading_Deploy_Status, !- Name
  zn_ne_09_n, !- Actuated Component Unique Name
  Window_Shading_Control, !- Actuated Component Type
  Control_Status; !- Actuated Component Control Type

```

! CONTROL ALGORITHMS

```

EnergyManagementSystem:Program,
  Set_Shade_Control_State2801, !- Name
  Set SPT_Value = @TrendValue SPT2801 1, !- Program Line 1
  IF Sensor8 > 100000, !- Program Line 2
  Set Sub_Surface_zn_ne_09_n_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A4
  ELSEIF Sensor8 < 49000 && SPT_Value > 0, !- A5
  Set Sub_Surface_zn_ne_09_n_Shading_Deploy_Status = Shade_Status_Off, !- A6
  ELSEIF Sensor8 > 49000 && Sensor8 < 100000 && SPT_Value > 0, !- A7
  Set Sub_Surface_zn_ne_09_n_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A8
  ELSE, !- A9
  Set Sub_Surface_zn_ne_09_n_Shading_Deploy_Status = Shade_Status_Off, !- A10
  ENDIF; !- A11

```

```

EnergyManagementSystem:OutputVariable,
  Erl_Shading_Control_Status2801, !- Name
  Sub_Surface_zn_ne_09_n_Shading_Deploy_Status, !- EMS Variable Name
  Averaged, !- Type of Data in Variable
  ZoneTimeStep; !- Update Frequency

```

```

EnergyManagementSystem:ProgramCallingManager,
  Init_Window_Shading_Device_Control_Constants2801, !- Name
  BeginNewEnvironment, !- EnergyPlus Model Calling Point
  InitializeShadeControlFlags2801; !- Program Name 1

```

EnergyManagementSystem:Program,
InitializeShadeControlFlags2801, !- Name
Set Shade_Status_None = 0.0 - 1.0, !- Program Line 1
Set Shade_Status_Off = 0.0, !- Program Line 2
Set Shade_Status_Interior_Blind_On = 6.0; !- <none>

!- ===== ALL OBJECTS IN CLASS: OUTPUT:VARIABLE =====

Output:Variable,*,Erl Shading Control Status2301,Timestep;
Output:Variable,*,Erl Shading Control Status2401,Timestep;
Output:Variable,*,Erl Shading Control Status2501,Timestep;
Output:Variable,*,Erl Shading Control Status2601,Timestep;
Output:Variable,*,Erl Shading Control Status2701,Timestep;
Output:Variable,*,Erl Shading Control Status2801,Timestep;

APPENDIX H: IES LM-83 SCRIPT

The following script, seen below, represents the blind operation coding to simulate IES LM-83 manual blind control algorithm. This object is used for the entire floor and all the facades.

```
#!/bin/bash

# Annual simulation of dynamic/complex fenestration systems under LM-83 guidelines. This script will generate its own
# folder structure beyond the starting directories required, which are outlined below.
#
# Version 1.0.3 June 3, 2014
#
# Changes:
# v.1.0
#   Eliminated post-dctimestep result transposition--too time consuming on large matrices.
#
# History:
# v.1.0 April 23, 2013
#
# Author: Alen Mahic, Ery Djunaedy (Integrated Design Lab University of Idaho)
# Copylefted (c) under GPL v.3 (http://opensource.org/licenses/GPL-3.0)
#
# In plain English: you are free to use this script, distribute it, make changes to it, as long as (1) you acknowledge
# Alen Mahic, Ery Djunaedy and the Integrated Design Lab as the original authors, and (2) you acknowledge that the script
# is provided as-is with absolutely no warranty, and that the authors and the University of Idaho are not liable to anything
# that happens or does not happen in relation to the use of this script.
#
# Radiance 4.2.a is required. (February 19th, 2013 NREL package)
# https://openstudio.nrel.gov/getting-started-developer/getting-started-radiance
#
# Usage: ./idl_lm83.sh -i [file] -m N -rz+/-N -clean -rtrace
#
# -i [file]   The main .rad file for the model, which pulls its geometry elements from the ./objects/ directory
#             and its windows from the ./objects/windows/ directory. Each window group is broken down into a
#             .rad file of its own with the filename matching the modifier name used for each defined polygon.
#             These two must match. Required input.
#
# -m N       Specifies the number of subdivisions of the sky. The Reinhart MF: setting where "N" is 1, 2, 3,
#             or 4. Optional input, the default value is 4.
#
# -rz+/-N    Specifies the orientation of the building in degrees. Make sure that there is no space between the
#             "-rz" argument and the +/- "N" value. Optional input, the default value is 0.
#
# -clean     This switch will clean the directory and delete all directories and files that were generated in
#             any previous runs. This includes the contents of the "results" folder.
#
# -rcontrib  This switch will enable the use of rcontrib for the direct sun analysis, otherwise it will use
#             rtrace with continuous skies generated by gendaylit (or gensky if gendaylit should fail) to
#             determine the direct sun exposure for the solar disc analysis. This method is much more time
#             consuming and takes ~10-15 times as long.
#
# -add       Inclusion of non-operated glazing/skylight openings.
#
# Assumed folder structure:
#
# ./
#   The main directory contains this script file and the primary .rad file of the model.
#
# ./data/
#   Contains the point analysis files.
#
# ./materials/
```

```

#     Contains the "materials.rad" file with the relevant material definitions for the model. The "glazing" and
#     "wall_mat" material identifiers are used in the script and assigned to the glazings and walls respectively.
#     These two must be defined in the "materials.rad" file. This directory also includes the .xml BSDF input files.
#
# ./objects/
#     Contains the geometry .rad files referenced by the primary model file in the main directory.
#
# ./objects/windows/
#     Contains the window group definitions, each in an individual .rad file with the filename matching the modifier
#     name used for each defined polygon. These two must match. The modifier convention requires that each modifier
#     include one of the following suffixes:
#         "_s" for a south-facing window group
#         "_w" for a west-facing window group
#         "_n" for a north-facing window group
#         "_e" for an east-facing window group
#
#         File example: ./objects/windows/windows_s.rad
#         Definition example: windows_s polygon window_name
#             0
#             0
#             12
#             0 0 0
#             2 0 0
#             2 0 2
#             0 0 2
#
# ./wea/
#     Contains the TMY3 weather files in .epw format.
#
# Assumed input files:
#
# ./[filename].rad
#     Primary model file.
#
# ./data/*.pts
#     All desired analysis point files.
#
# ./materials/materials.rad
#     Materials file.
#
# ./materials/singleclear.xml
#     BSDF file for the open condition. The "singleclear" name is also assigned to the $bsdf_open variable in the script.
#
# ./materials/venetian_75.xml
#     BSDF file for the closed condition. The "venetian_75" name is also assigned to the $bsdf_closed variable in the script.
#
# ./objects/*.rad
#     All relevant geometry files referenced by the primary model file.
#
# ./objects/windows/*.rad
#     All desired window groups separated into .rad files, taking their filenames from the modifiers used in each one.
#
# ./wea/*.epw
#     All desired weather files.
#
# Results:
#     The outputs will be deposited in the ./results/ directory. The naming conventions for the operated annual illuminance
#     matrix, the operation schedule files, and the LM-83 metric calculations are as follows:
#     [pointfile]--[weatherfile]--m[N]--final.ill
#     [pointfile]--[weatherfile]--m[N]--final_blinds_sched.dat
#     LM83_metrics.dat
#
# Non-operated glazing and/or skylight material assignments:
#     The following modifier names are to be assigned to geometries that are windows or skylights, but not part of any
#     operated window groups:
#     "nonoperated_glaz" (Glazing)
#     "nonoperated_sky" (Skylight)
#     Currently this script supports one material assignment for each, but can be modified to accomodate more variables
#     for both types.
#
#

```

```

# Material options:
# Specify the identifier of the glazing material definition.. mat_glaz="glazing"
mat_glaz="CLEAR_3_glass"
# Specify the identifier of the wall material definition.. mat_wall="wall_mat"
mat_wall="wall"
# Specify the name of the "open" condition BSDF file without the file extension.. bsdf_open="singleclear"
bsdf_open="open"
# Specify the name of the "closed" condition BSDF file without the file extension.. bsdf_closed="venetian_75"
bsdf_closed="closed"
# Specify the name of the skylight material, assuming that "nonoperated_sky" has been assigned to some geometries in the ./objects folder.
mat_sky="ClearGlazing_70_Shading"
# If the -add argument is specified, the script will also look for the "nonoperated_glaz" modifier. These surfaces will be simulated separately
of the operable window groups and then later added as the non-operated contribution to the total light in the space.

# Read script arguments..
args=$(echo $@ |sed "s/^ *//;s/ *$//;s/\\{1,\\}/ /g;s/\\{1,\\} /-/g;s/ -/t-g/")

# SOS..
help=$(echo $@ |sed "s/^ *//;s/ *$//;s/\\{1,\\}/ /g;s/\\{1,\\}/\\{1,\\}/g;s/\\{1,\\} /-/g;s/ -/t-g/" |tr '\t' '\n' |grep -x -e "-{1,\\}help" |tail -1 |sed -e "s/^
\\{1,\\}/")
# Clean switch..
clean=$(echo $@ |sed "s/^ *//;s/ *$//;s/\\{1,\\}/ /g;s/\\{1,\\}/\\{1,\\}/g;s/\\{1,\\} /-/g;s/ -/t-g/" |tr '\t' '\n' |grep -x -e "-{1,\\}clean" |tail -1 |sed -e "s/^
\\{1,\\}/")

# Blinds operation parameters..
sd_trigger="1000"
sd_trigger_per="2"
da_trigger="300"
sda_trigger="50"
ase_trigger_lux="1000"
ase_trigger_hours="250"
period_start="9"
period_end="18"
period_int=$(echo $period_end $period_start |awk '{printf("%.0f", $1-$2)}')

# Directories
windir="./objects/windows"
ptsdir="./data"
if [ "$(ls $ptsdir)" == "" ];then ">> Error: The \"$ptsdir\" is empty.";exit 0;fi;
matdir="./materials"
if [ "$(ls $matdir)" == "" ];then ">> Error: The \"$matdir\" is empty.";exit 0;fi;
weadir="./wea"
if [ "$(ls $weadir)" == "" ];then ">> Error: The \"$weadir\" is empty.";exit 0;fi;
resdir="./results"
resdir_dat="./results/dat"
resdir_ill="./results/ill"
resdir_sd="./results/solardisc"
resdir_add="./results/add"
optdir="./options"
skydir="./skies"
tmpdir="./temp"
logdir="./log"

# Temp and material outputs..
dmx="./materials/inherit_dmx.rad"
vmx="./materials/inherit_vmx.rad"
solardisc="./materials/inherit_solardisc.rad"
tmp_solardisc="inherit_solardisc.rad"
tmp_additional="inherit_additional.rad"
tmp_sky="temp_sky.rad"
tmp_wea="temp_weather.wea"

scriptname=$(basename $0)

# Print help..
if [ "$help" == "help" ];then
#help_man=$(head -108 $scriptname |tail -n+2 |sed -e "s/#/ /g")
#echo -e $help_man
head -98 $scriptname |tail -n+2 |sed -e "s/#/>/g" |more; echo;

```

```

    exit 0;
fi

# Clean the directory..
if [ "$clean" == "clean" ];then
    rm -f -r $tmpdir $resdir $skeydir $optdir $dmx $vmx $solardisc
    rmlist=$(ls ./ |grep -i -e ".oct$")
    for f in $rmlist; do rm -f -r $f;done;
    rmlist=$(ls $weadir |grep -v -i -e ".epw$")
    for f in $rmlist; do rm -f -r $weadir/$f;done;
    echo "> Directory cleaned."
    exit 0;
fi

# Parse model and parameter arguments..
model=$(echo $@ |sed "s/^ *//;s/ *$//;s/ \{1,\} /g;s/\{1,\} //g;s/\{1,\} /-g;s/ -/t-g" |tr '\t' '\n' |grep -e "-\{1,\}i" |tail -1 |sed "s/\{1,\}i
//;s/\{1,\} //;s/\{1,\} //;s/\{1,\} //;s/\{1,\} //;s/\{1,\} //;")
if [ ! "$model" ];then echo -e ">> Error: Please specify the input model.\n Help: ./scriptname -help";exit 0;elif [ ! -f $model ];then echo
">> Error: The specified file does not exist.";exit 0;elif [ ! ".${model##*}" == ".rad" ];then echo -e ">> Error: The specified file is not in
.rad format.";exit 0;fi;
granularity=$(echo $@ |sed "s/^ *//;s/ *$//;s/ \{1,\} /g;s/\{1,\} //g;s/\{1,\} /-g;s/ -/t-g" |tr '\t' '\n' |grep -e "-\{1,\}m" |tail -1 |sed "s/-
\{1,\}m //")
if [ ! "$granularity" ];then granularity=4;elif [ [ $granularity == *[0-9]* ] ];then if [ $granularity -gt 4 ]||[ $granularity -lt 1 ];then echo ">>
Warning: The specified granularity is out of range, using default value. [4]";granularity=4;fi;else echo ">> Warning: The specified
granularity is invalid, using default value. [4]";granularity=4;fi;
rotation=$(echo $@ |sed "s/^ *//;s/ *$//;s/ \{1,\} /g;s/\{1,\} //g;s/\{1,\} /-g;s/ -/t-g" |tr '\t' '\n' |grep -e "-\{1,\}rz" |tail -1 |sed "s/-
\{1,\}rz //")
if [ ! "$rotation" ];then rotation=0;rtag="";else rtag="--rz$rotation";fi;
#rtrace=$(echo $@ |sed "s/^ *//;s/ *$//;s/ \{1,\} /g;s/\{1,\} //g;s/\{1,\} /-g;s/ -/t-g" |tr '\t' '\n' |grep -x -e "-\{1,\}rtrace" |tail -1 |sed -e "s/^
\{1,\} //")
rcontrib=$(echo $@ |sed "s/^ *//;s/ *$//;s/ \{1,\} /g;s/\{1,\} //g;s/\{1,\} /-g;s/ -/t-g" |tr '\t' '\n' |grep -x -e "-\{1,\}rcontrib" |tail -1 |sed -e
"s/\{1,\} //")

# Model and materials..
modelname=$(basename $model .${model##*})
materials="/materials/materials.rad"
if [ ! -f $materials ];then echo ">> Error: The \"$materials\" file does not exist.";exit 0;fi;
if [ [ ! $(cat $materials |sed "s/\t*/g;s/ */g" |grep -e "$mat_glaz$") ] ]; then echo ">> Error: The \"$mat_glaz\" material definition was not
found in the \"$materials\" file.";exit 0;fi;
if [ [ ! $(cat $materials |sed "s/\t*/g;s/ */g" |grep -e "$mat_wall$") ] ]; then echo ">> Error: The \"$mat_wall\" material definition was not
found in the \"$materials\" file.";exit 0;fi;
if [ "$mat_sky" ];then
    add=$(echo $@ |sed "s/^ *//;s/ *$//;s/ \{1,\} /g;s/\{1,\} //g;s/\{1,\} /-g;s/ -/t-g" |tr '\t' '\n' |grep -x -e "-\{1,\}add" |tail -1 |sed -e "s/^
\{1,\} //")
    if [ [ ! $(cat $materials |sed "s/\t*/g;s/ */g" |grep -e "$mat_sky$") ] ]; then echo ">> Error: The \"$mat_sky\" material definition was not
found in the \"$materials\" file.";exit 0;fi;
fi
op=$(echo $@ |sed "s/^ *//;s/ *$//;s/ \{1,\} /g;s/\{1,\} //g;s/\{1,\} /-g;s/ -/t-g" |tr '\t' '\n' |grep -x -e "-\{1,\}op" |tail -1 |sed -e "s/^
\{1,\} //")

# Make relevant directories..
mkdir -p $resdir $matdir $optdir $skeydir $resdir_dat $resdir_ill $resdir_sd $resdir_add $tmpdir $logdir

# Log
timestart=$(date +%F-%H%M%S)
log="$logdir/log_${timestart}.log"
echo "[${timestart}] Starting.. > $log

dir=$( cd "$( dirname "${BASH_SOURCE[0]}" )" && pwd )
echo -e "> Running.\n> Use the following command in a new terminal to follow the log file live:\n tail -f ${dir}/log/${dir}/log |tail -
1)"

# Lists for loops..
winlist=$(ls $windir |grep -i -e ".rad$")
ptslist=$(ls $ptsdir |grep -i -e ".pts$")
bsdflist=$(ls $matdir |grep -i -e ".xml$")
wealist=$(ls $weadir |grep -i -e ".epw$")

# Custom operation..
if [ $op ];then

```

```

echo "Operating using input.csv..."

exit;
fi

# Generate skies..
sky="./skies/sky_white_360.rad"
sky_blank="./skies/sky.rad"
echo -e "void glow sky_glow 0 0 4 1 1 1 0\nsky_glow source sky 0 0 4 0 0 1 360" > $sky
echo -e "skyfunc glow sky_mat 0 0 4 1 1 1 0\nsky_mat source sky 0 0 4 0 0 1 180\nskyfunc glow ground_glow 0 0 4 1 .8 .5 0\nground_glow
source ground 0 0 4 0 0 -1 180" > $sky_blank
echo "[$(date +%F-%H%M%S)] Sky files generated." >> $log

# Generate options files..
opt="$Soptdir/general.opt"
opt_sd="$Soptdir/solar.opt"
opt_sd_sp="$Soptdir/solar_sp.opt"
echo "-ab 6 -ad 4096 -as 1024 -ar 256 -aa 0.1 -lw 0.0003 -dt 0 -ds 0.1" > $opt
echo "-ab 0 -ad 512 -as 128 -ar 128 -aa 0.1" > $opt_sd
echo "-ab 1 -ad 4096 -as 1024 -ar 1024 -aa 0.08 -lw 0.0003 -dt 0" > $opt_sd_sp
echo "[$(date +%F-%H%M%S)] Options files generated." >> $log

# Define the light material for the view matrix and define the materials required for both the daylight and view matrices.
rm -f -r $dmx $vmx $solardisc
echo "void light window_vmx 0 0 3 1 1 1" >> $vmx
for win in $winlist; do
    winname=$(basename ${win} .${win##*.})
    # Modifiers must match the filenames of each window group file in ./objects/windows/
    echo "inherit alias $winname window_vmx" >> $vmx
    echo "inherit alias $winname $mat_glaz" >> $dmx
    echo "inherit alias $winname $mat_wall" >> $solardisc
done
echo "inherit alias nonoperated_glaz $mat_glaz" >> $vmx
echo "inherit alias nonoperated_glaz $mat_wall" >> $dmx
echo "inherit alias nonoperated_glaz $mat_wall" >> $solardisc
echo "inherit alias nonoperated_sky $mat_sky" >> $vmx
echo "inherit alias nonoperated_sky $mat_wall" >> $dmx
echo "inherit alias nonoperated_sky $mat_wall" >> $solardisc
echo "[$(date +%F-%H%M%S)] Materials assigned." >> $log

oconv $materials $dmx $model $sky > ${modelName}_dmx.oct
oconv $materials $vmx $model > ${modelName}_vmx.oct
echo "[$(date +%F-%H%M%S)] OCTREES generated: ./${modelName}_dmx.oct ./${modelName}_vmx.oct" >> $log

modlist=""

for win in $winlist; do
    winname=$(basename ${win} .${win##*.})
    win_o=$(echo $winname |sed -e "s/_/_/g;s/_/_/g;s/_/_/g" |rev |cut -d '_' -f1)
    unknown=0
    # Modifiers must match the filenames of each window group file in ./objects/windows/
    if [ $(echo $win_o |grep -i -e "s") ];then viewdir="0 -1 0";elif [ $(echo $win_o |grep -i -e "w") ];then viewdir="-1 0 0";elif [ $(echo $win_o
|grep -i -e "n") ];then viewdir="0 1 0";elif [ $(echo $win_o |grep -i -e "e") ];then viewdir="1 0 0";else echo "> Warning: \"$winname\"
orientation unknown.";unknown=1;fi;
    if [ $unknown -eq 0 ];then
        # Generate the daylight matrix..
        echo "[$(date +%F-%H%M%S)] Generating daylight matrix for \"${winname}\" with an \"MF:${granularity}\" setting." >> $log
        genklemsamp -vd $viewdir $windir/$win |rcontrib -fo -faf -c 1000 -e MF:$granularity -f reinhart.cal -o
        $resdir/${winname}_m${granularity}.dmx -b rbin -bn Nrbins -m sky_glow ${modelName}_dmx.oct
        echo "[$(date +%F-%H%M%S)] Daylight matrix generated: $resdir/${winname}_m${granularity}.dmx" >> $log
        modlist="${modlist} -b kbin$(echo $win_o |tr '[:lower:]' '[:upper:]') -m $winname"
    fi
done

# Generate the view matrices..
if [ ! "$modlist" ];then echo ">> Error: Material modifiers could not be determined for the view matrix.";exit 0;
else
    for pts in $ptslist; do
        ptsname=$(basename ${pts} .${pts##*.})
        cat $ptsdir/$pts |sed -e "/^$/d" > $tmpdir/$pts
    done
fi

```



```

    echo "" >> $tmpdir/$pts
    echo "[$(date +%F-%H%M%S)] Generating view matrix for \"${ptsname}\" analysis grid." >> $log
    cat $tmpdir/$pts | rcontrib -fo -faf -f klems_int.cal -bn Nkbins -o $resdir/${ptsname}_%.vmx $modlist -I+ @$opt
${modelName}_vmx.oct
    echo "[$(date +%F-%H%M%S)] View matrices generated: $resdir/${ptsname}_*.vmx" >> $log
done
fi

# Parse EPW weather file into WEA format for use with gendaymtx..
for wea in $wealist; do
    weafile="$weadir/$wea"
    weaname=$(basename $wea .${wea##*.})
    timestep="$weadir/${weaname}_timestep.dat"
    # Location is the first line of the EPW header..
    loc=$(head -1 $weafile)
    # Data period is the 8th line of the EPW header..
    dataper=$(head -8 $weafile | tail -1)
    lat=$(echo $loc | cut -d ',' -f7)
    longitude=$(echo $loc | cut -d ',' -f8)
    # EPW lists longitude + to the east, Radiance + to the west..
    lon=$(echo $longitude | rcalc -e '$1=-1*$1')
    meridian=$(echo $loc | cut -d ',' -f9)
    # EPW lists time zone in hours, but we need degrees..
    mer=$(echo $meridian | rcalc -e '$1=$1*-15')
    # WEA header format.. weather_data_file_units is either
    # field 2 (described as "#Number" in the EPW format documentation) or
    # field 3 (described as "#Number Records/Intervals in an hour" in the EPW format documentation).
    # [http://apps1.eere.energy.gov/buildings/energyplus/pdfs/weatherdatainformation.pdf]
    # This script uses field 2.
    echo -e "place $(echo $loc | cut -d ',' -f2)_$(echo $loc | cut -d ',' -f4)\nlatitude $lat\nlongitude $lon\nsite_elevation
$(echo $loc | cut -d ',' -f10)\nweather_data_file_units $(echo $dataper | cut -d ',' -f2)" > "$weadir/${weaname}.wea"
    tail -n +9 $weafile | rcalc -t, -e '$1=$2;$2=$3;$3=$4;$4=$5;$5=$6' | sed -e 's/,/ /g' >> $weadir/$weaname.wea
    tail -n +7 $weadir/$weaname.wea | cut -d ' ' -f1-3 > $timestep
    # Generate sky vector matrix..
    if [ -f $weadir/${weaname}--m${granularity}${rzttag}.smx ];then echo ">> Warning: Existing sky vector matrix found:
$weadir/${weaname}--m${granularity}${rzttag}.smx";
    else
        echo "[$(date +%F-%H%M%S)] Generating sky vector matrix with an \"-m ${granularity}\" setting" >> $log
        gendaymtx -r $(awk -v rotation=$rotation 'BEGIN{print (rotation*-1);}' -m $granularity -of $weadir/$weaname.wea >
"$weadir/${weaname}--m${granularity}${rzttag}.smx"
        echo "[$(date +%F-%H%M%S)] Sky vector matrix generated: $weadir/${weaname}_m${granularity}${rzttag}.smx" >> $log
    fi
    # Generate direct sun sky vector matrix..
    if [ -f $weadir/${weaname}--m4${rzttag}--sol.smx ];then echo ">> Warning: Existing direct sun sky vector matrix found:
$weadir/${weaname}--m4${rzttag}--sol.smx";
    elif [ ! $rtrace ];then
        #else
        echo "[$(date +%F-%H%M%S)] Generating direct sun sky vector matrix with an \"-m 4\" setting" >> $log
        gendaymtx -d -r $(awk -v rotation=$rotation 'BEGIN{print (rotation*-1);}' -m 4 -of $weadir/$weaname.wea > "$weadir/${weaname}--
m4${rzttag}--sol.smx"
        echo "[$(date +%F-%H%M%S)] Direct sun sky vector matrix generated: $weadir/${weaname}--m4${rzttag}--sol.smx" >> $log
    fi
done

# Contribution from non-operated window openings
if [ $add ];then
    cat $solar_disc > $tmpdir/$tmp_additional
    echo "inherit alias nonoperated_glaz $mat_glaz" >> $tmpdir/$tmp_additional
    echo "inherit alias nonoperated_sky $mat_sky" >> $tmpdir/$tmp_additional
    echo "[$(date +%F-%H%M%S)] Generating OCTREE for single-phase non-BSDF light source contribution." >> $log
    oconv -w $materials $tmpdir/$tmp_additional $model $sky > ${modelName}_dmx_add.oct
    for pts in $ptslist; do
        ptsname=$(basename $pts .${pts##*.})
        echo "[$(date +%F-%H%M%S)] Generating single-phase solar disc daylight matrix for single-phase non-BSDF light source
contribution with an \"MF:${granularity}\" setting." >> $log
        rcontrib -fo -faf -I+ -e MF:${granularity} -f reinhart.cal -o $resdir/${modelName}_m${granularity}_add.dmx -b rbin -bn Nrbins -m
sky_glow @$opt ${modelName}_dmx_add.oct < $tmpdir/$pts
        echo "[$(date +%F-%H%M%S)] Single-phase non-BSDF light source contribution daylight matrix generated:
$resdir/${modelName}_m${granularity}_add.dmx" >> $log
    for wea in $wealist; do

```

```

weaname=$(basename $wea .${wea##*.})
outname="${ptsname}-${weaname}-m${granularity}${rzttag}"
timestep="$weadir/${weaname}_timestep.dat"
#echo -n "" > "$resdir_add/${outname}.ill"
echo -n "" > "$resdir_add/${outname}.dat"
echo "[$(date +%F-%H%M%S)] Running single-phase non-BSDF light source contribution dctimestep on:
$resdir/${modelName}_m${granularity}_add.dmx $weadir/${weaname}-m${granularity}${rzttag}.smx" >> $log
save_IFS=$IFS
dctimestep -n 8760 -if $resdir/${modelName}_m${granularity}_add.dmx $weadir/${weaname}-m${granularity}${rzttag}.smx |sed -
e '/^$/d' |tail -n +6 |sed -e "s/^\t/g;s/^ //g" |while read line; do IFS=$IFS;echo $line |awk -F"\t" '{for(i=1;i<=NF;i++){split($i,a,"
");conv=(179*(a[1]*0.265+a[2]*0.670+a[3]*0.065));if(conv==0){printf("%.0f ",conv)}else{printf("%.2f ",conv)}}}END{print ""}' |sed -e
"s/ /" >> "$resdir_add/${outname}.dat";done;
IFS=$save_IFS
echo "[$(date +%F-%H%M%S)] Single-phase non-BSDF light source contribution dctimestep finished:
$resdir_add/${outname}.dat" >> $log
done
done
fi

# Pull it all together with dctimestep..
for wea in $wealist; do

weaname=$(basename $wea .${wea##*.})
timestep="$weadir/${weaname}_timestep.dat"
for pts in $ptslist; do

ptsname=$(basename $pts .${pts##*.})
for bsdf in $bsdflist; do

bsdfname=$(basename $bsdf .${bsdf##*.})
for win in $winlist; do
winname=$(basename $win .${win##*.})
outname="$ptsname}-${winname}-${bsdfname}-${weaname}-m${granularity}${rzttag}"
echo -n "" > "$resdir_dat/${outname}.dat"
echo "[$(date +%F-%H%M%S)] Running dctimestep on: $resdir/${ptsname}_${winname}.vmx $matdir/$bsdf
$resdir/${winname}_m${granularity}.dmx $weadir/${weaname}-m${granularity}${rzttag}.smx" >> $log
save_IFS=$IFS
dctimestep -n 8760 -if $resdir/${ptsname}_${winname}.vmx $matdir/$bsdf $resdir/${winname}_m${granularity}.dmx
$weadir/${weaname}-m${granularity}${rzttag}.smx |sed -e '/^$/d' |tail -n +6 |sed -e "s/^\t/g;s/^ //g" |while read line; do IFS=$IFS;echo $line
|awk -F"\t" '{for(i=1;i<=NF;i++){split($i,a," ");conv=(179*(a[1]*0.265+a[2]*0.670+a[3]*0.065));if(conv==0){printf("%.0f
",conv)}else{printf("%.2f ",conv)}}}END{print ""}' |sed -e "s/ /:/s/0/g" >> "$resdir_dat/${outname}.dat";done;
IFS=$save_IFS
echo "[$(date +%F-%H%M%S)] dctimestep finished: $resdir_dat/${outname}.dat" >> $log

if [ $add ];then
echo "[$(date +%F-%H%M%S)] Adding contribution of non-BSDF sources to $resdir_dat/${outname}.dat" >> $log
#awk '
#FNR==NR {
#for(i=1; i<=NF; i++)
# _[FNR,i]=$i
# next
#}
#{
#for(i=1; i<=NF; i++)
# printf("%d%s", $i+_[FNR,i], (i==NF) ? "\n" : FS);
#}' $resdir_dat/${outname}.dat $resdir_add/${ptsname}-${weaname}-m${granularity}${rzttag}.dat >
$tmkdir/${outname}.dat
res_cnum=$(head -1 $resdir_dat/${outname}.dat |tr ' ' '\n' |wc -l)
res_cnum_add=$(head -1 $resdir_add/${ptsname}-${weaname}-m${granularity}${rzttag}.dat |tr ' ' '\n' |wc -l)
export res_cnum;
paste $resdir_dat/${outname}.dat $resdir_add/${ptsname}-${weaname}-m${granularity}${rzttag}.dat |perl -alne 'print join "
", map {${F$_} + ${F$_}$ENV{res_cnum}} 0..$ENV{res_cnum}-1' > $tmkdir/${outname}.dat
if [ "$res_cnum" != "$res_cnum_add" ];then
echo "[$(date +%F-%H%M%S)] Warning: Number of columns do not match: $resdir_dat/${outname}.dat [$res_cnum] and
$resdir_add/${ptsname}-${weaname}-m${granularity}${rzttag}.dat [$res_cnum_add]" >> $log
fi
echo "[$(date +%F-%H%M%S)] Non-BSDF sources added to $resdir_dat/${outname}.dat" >> $log

mv $resdir_dat/${outname}.dat $resdir_dat/${outname}_orig.dat
#rm $resdir_dat/${outname}.dat

```

```

        mv $tmpdir/${outname}.dat $resdir_dat/${outname}.dat
    fi
done
done
done
done

echo "" >> $log

# Solar disc analysis..
echo "[$(date +%F-%H%M%S)] Starting solardisc analysis.." >> $log
if [[ ! $rcontrib ]];then
    # Rtrace solar disc analysis..
    wealist=$(ls $weadir |grep ".wea$")
    for pts in $ptslist; do
        ptsname=$(basename $pts) .${pts##*.})
        npts=$(cat $tmpdir/$pts |sed -e "/^$/d" |wc -l)
        nullvec=""
        for i in $(seq 1 $npts); do nullvec="{nullvec}0 ";done;
        for win in $winlist; do
            winname=$(basename $win) .${win##*.})
            cat $solardisc > $tmpdir/$tmp_solardisc
            echo "inherit alias $winname $mat_glaz" >> $tmpdir/$tmp_solardisc
            for wea in $wealist; do
                weaname=$(basename $wea) .${wea##*.})
                tail -n +7 $weadir/$wea > $tmpdir/$tmp_wea
                echo -n "" > $resdir_sd/${ptsname}--${winname}--${weaname}--m${granularity}${rztag}.ill
                echo "[$(date +%F-%H%M%S)] Starting solar disc analysis for \"${modelname}_${winname}\" >> $log
                while read line; do
                    month=$(echo $line |cut -d ' ' -f1)
                    day=$(echo $line |cut -d ' ' -f2)
                    time=$(echo $line |cut -d ' ' -f3)
                    irr_dir=$(echo $line |cut -d ' ' -f4)
                    irr_diff=$(echo $line |cut -d ' ' -f5)
                    lat=$(head -2 $weadir/$wea |tail -1 |cut -d ' ' -f2)
                    lon=$(head -3 $weadir/$wea |tail -1 |cut -d ' ' -f2)
                    mer=$(head -4 $weadir/$wea |tail -1 |cut -d ' ' -f2)
                    if [ "$Sirr_dir $Sirr_diff" == "0 0" ];then
                        echo "$nullvec" >> $resdir_sd/${ptsname}--${winname}--${weaname}--m${granularity}${rztag}.ill
                        echo -n "" > $tmpdir/$tmp_sky
                        echo -e "$month\t$day\t$time\t | $Sirr_dir | $Sirr_diff | EMPTY" >> $log
                    else
                        warnchk=""
                        warnchk=$(gendaylit $month $day $time -a $lat -o $lon -m $mer -W $Sirr_dir $Sirr_diff 2>&1 |head -2 |grep -i "range
warning")
                        if [ "$warnchk" == "" ];then
                            echo "!gendaylit $month $day $time -a $lat -o $lon -m $mer -W $Sirr_dir $Sirr_diff -w |xform -rz $(awk -v rotation=$rotation
'BEGIN{print (rotation*-1);})" > $tmpdir/$tmp_sky
                            echo "" >> $tmpdir/$tmp_sky
                            cat $sky_blank >> $tmpdir/$tmp_sky
                            echo -e "$month\t$day\t$time\t | $Sirr_dir | $Sirr_diff | GENDAYLIT" >> $log
                        elif [ $Sirr_dir -eq 0 ];then
                            echo -n "" > $tmpdir/$tmp_sky
                            echo -e "$month\t$day\t$time\t | $Sirr_dir | $Sirr_diff | EMPTY (dir_nor=0)" >> $log
                        else
                            echo "!gensky $month $day $time +s -a $lat -o $lon -m $mer |xform -rz $(awk -v rotation=$rotation 'BEGIN{print
(rotation*-1);})" > $tmpdir/$tmp_sky
                            echo "" >> $tmpdir/$tmp_sky
                            cat $sky_blank >> $tmpdir/$tmp_sky
                            echo -e "$month\t$day\t$time\t | $Sirr_dir | $Sirr_diff | GENSKY" >> $log
                        fi
                    oconv -w $materials $tmpdir/$tmp_solardisc $model $tmpdir/$tmp_sky > $tmpdir/${modelname}_${winname}.oct
                    rtrace -I -h -w @${opt_sd} $tmpdir/${modelname}_${winname}.oct < $tmpdir/$pts |rcalc -e
                    '$1=179*($1*0.265+$2*0.670+$3*0.065)' |tr '\n' ' ' |sed -e "s/$/n/" >> $resdir_sd/${ptsname}--${winname}--${weaname}--
                    m${granularity}${rztag}.ill
                    #rtrace -I -h -w @${opt_sd} $tmpdir/${modelname}_${winname}.oct < $tmpdir/$pts |rcalc -e
                    '$1=179*($1*0.265+$2*0.670+$3*0.065)' |awk 'if($1==0){printf("%.0f ",$1)}else{printf("%.2f ",$1)}' |sed -e "s/$/n;/s/^/$month $day
                    $time /" >> $resdir_sd/${ptsname}--${winname}--${weaname}--m${granularity}${rztag}.ill
                fi
            done < "$tmpdir/$tmp_wea"

```

```

        # Transpose rtrace results..
        echo "[$(date +%F-%H%M%S)] Transposing \"$resdir_sd/${ptsname}--${winname}--${weaname}--
m${granularity}${rzttag}.ill\" >> $log
        rcollate -h -fa1 -t $resdir_sd/${ptsname}--${winname}--${weaname}--m${granularity}${rzttag}.ill |tr 't' '>' >
$resdir_sd/${ptsname}--${winname}--${weaname}--m${granularity}${rzttag}.dat
        echo "[$(date +%F-%H%M%S)] Transpose finished: $resdir_sd/${ptsname}--${winname}--${weaname}--
m${granularity}${rzttag}.ill\" >> $log
        done
    done
done
else
# Single-phase rcontrib solar disc analysis..
wealist=$(ls $weadir |grep ".wea$")
for pts in $ptslist; do
    ptsname=$(basename ${pts} .${pts##*.})
    npts=$(cat $tmpdir/$pts |sed -e '/^$/d' |wc -l)
    nullvec=""
    for i in $(seq 1 $npts); do nullvec="$ {nullvec}0 ";done;
    for win in $winlist; do
        winname=$(basename $win .${win##*.})
        # Generate single-phase daylight matrix for solardisc analysis..
        cat $solardisc > $tmpdir/$tmp_solardisc
        echo "inherit alias $winname $mat_glaz" >> $tmpdir/$tmp_solardisc
        echo "[$(date +%F-%H%M%S)] Generating OCTREE for single-phase solardisc analysis for \"${winname}\" >> $log
        oconv -w $materials $tmpdir/$tmp_solardisc $model $sky > ${modelname}_dmx_sol.occ
        echo "[$(date +%F-%H%M%S)] Generating single-phase solardisc daylight matrix for \"${winname}\" with an \"MF:4\" setting."
    >> $log
        rcontrib -fo -faf -It -e MF:4 -f reinhart.cal -o $resdir/${winname}_m4_sol.dmx -b rbin -bn Nrbins -m sky_glow @$ {opt_sd_sp}
    ${modelname}_dmx_sol.occ < $tmpdir/$pts
        echo "[$(date +%F-%H%M%S)] Single-phase solardisc daylight matrix generated: $resdir/${winname}_m4_sol.dmx\" >> $log

        for wea in $wealist; do
            weaname=$(basename $wea .${wea##*.})
            outname="$ {ptsname}--${winname}--${weaname}--m4${rzttag}"
            timestep="$weadir/${weaname}_timestep.dat"
            echo -n "" > "$resdir_sd/${outname}.ill"
            echo -n "" > "$resdir_sd/${outname}.dat"
            echo "[$(date +%F-%H%M%S)] Running single-phase solardisc dctimestep on: $resdir/${winname}_m4_sol.dmx
$weadir/${weaname}--m4${rzttag}--sol.smx\" >> $log
            save_IFS=$IFS
            dctimestep -n 8760 -if $resdir/${winname}_m4_sol.dmx $weadir/${weaname}--m4${rzttag}--sol.smx |sed -e '/^$/d' |tail -n +6 |sed
-e "s/^\t/g;s/^\t/g" |while read line; do IFS=$IFS;echo $line |awk -F"t" '{for(i=1;i<=NF;i++){split($i,a,"
");conv=(179*(a[1]*0.265+a[2]*0.670+a[3]*0.065));if(conv==0){printf("%.0f ",conv)}else{printf("%.2f ",conv)}}}END{print ""}' |sed -e
"s/ $/" >> "$resdir_sd/${outname}.dat";done;
            IFS=$save_IFS
            echo "[$(date +%F-%H%M%S)] Single-phase solardisc dctimestep finished: $resdir_sd/${outname}.dat\" >> $log
        done
    done
done
done
done
fi

if [ $add ];then
# Rtrace solar disc analysis for non-operated windows..
wealist=$(ls $weadir |grep ".wea$")
for pts in $ptslist; do
    ptsname=$(basename ${pts} .${pts##*.})
    npts=$(cat $tmpdir/$pts |sed -e '/^$/d' |wc -l)
    nullvec=""
    for i in $(seq 1 $npts); do nullvec="$ {nullvec}0 ";done;
    for wea in $wealist; do
        weaname=$(basename $wea .${wea##*.})
        tail -n +7 $weadir/$wea > $tmpdir/$tmp_wea
        echo -n "" > $resdir_sd/${ptsname}--nonoperated--${weaname}--m${granularity}${rzttag}.ill
        echo "[$(date +%F-%H%M%S)] Starting solar disc analysis for \"${modelname}_${ptsname}_nonoperated\" >> $log
        while read line; do
            month=$(echo $line |cut -d ' ' -f1)
            day=$(echo $line |cut -d ' ' -f2)
            time=$(echo $line |cut -d ' ' -f3)
            irr_dir=$(echo $line |cut -d ' ' -f4)
            irr_diff=$(echo $line |cut -d ' ' -f5)

```

```

lat=$(head -2 $weadir/$wea |tail -1 |cut -d ' ' -f2)
lon=$(head -3 $weadir/$wea |tail -1 |cut -d ' ' -f2)
mer=$(head -4 $weadir/$wea |tail -1 |cut -d ' ' -f2)
if [ "$Sirr_dir $Sirr_diff" == "0 0" ];then
    echo "$nullvec" >> $resdir_sd/${ptsname}--nonoperated--${weaname}--m${granularity}${rzttag}.ill
    echo -n "" > $tmpdir/$tmp_sky
    echo -e "$month\t$day\t$time\t | $Sirr_dir | $Sirr_diff | EMPTY" >> $log
else
    warnchk=""
    warnchk=$(gendaylit $month $day $time -a $lat -o $lon -m $mer -W $Sirr_dir $Sirr_diff 2>&1 |head -2 |grep -i "range warning")
    if [ "$Swarnchk" == "" ];then
        echo "!gendaylit $month $day $time -a $lat -o $lon -m $mer -W $Sirr_dir $Sirr_diff -w |xform -rz $(awk -v rotation=$rotation
'BEGIN{print (rotation*-1);}') > $tmpdir/$tmp_sky
        echo "" >> $tmpdir/$tmp_sky
        cat $sky_blank >> $tmpdir/$tmp_sky
        echo -e "$month\t$day\t$time\t | $Sirr_dir | $Sirr_diff | GENDAYLIT" >> $log
    elif [ $Sirr_dir -eq 0 ];then
        echo -n "" > $tmpdir/$tmp_sky
        echo -e "$month\t$day\t$time\t | $Sirr_dir | $Sirr_diff | EMPTY (dir_nor=0)" >> $log
    else
        echo "!gensky $month $day $time +s -a $lat -o $lon -m $mer |xform -rz $(awk -v rotation=$rotation 'BEGIN{print (rotation*-
1);}') > $tmpdir/$tmp_sky
        echo "" >> $tmpdir/$tmp_sky
        cat $sky_blank >> $tmpdir/$tmp_sky
        echo -e "$month\t$day\t$time\t | $Sirr_dir | $Sirr_diff | GENSKY" >> $log
    fi
    oconv -w $materials $tmpdir/$tmp_additional $model $tmpdir/$tmp_sky > $tmpdir/${modelname}_nonoperated.oct
    rtrace -I -h -w @$opt_sd $tmpdir/${modelname}_nonoperated.oct < $tmpdir/$pts |rcalc -e
'$1=179*($1*0.265+$2*0.670+$3*0.065)' |tr '\n' ' ' |sed -e "s/$/\n/" >> $resdir_sd/${ptsname}--nonoperated--${weaname}--
m${granularity}${rzttag}.ill
    fi
    done < "$tmpdir/$tmp_wea"
done
# Transpose rtrace results..
echo "[$(date +%F-%H%M%S)] Transposing \"$resdir_sd/${ptsname}--nonoperated--${weaname}--m${granularity}${rzttag}.ill\"" >>
$log
    rcollate -h -fa1 -t $resdir_sd/${ptsname}--nonoperated--${weaname}--m${granularity}${rzttag}.ill |tr '\t' ' ' > $resdir_sd/${ptsname}--
nonoperated--${weaname}--m${granularity}${rzttag}.dat
    echo "[$(date +%F-%H%M%S)] Transpose finished: $resdir_sd/${ptsname}--nonoperated--${weaname}--
m${granularity}${rzttag}.ill" >> $log
done
fi

echo "" >> $log
echo "[$(date +%F-%H%M%S)] Starting blinds operation.." >> $log

# Blinds operation..
delimiter=" "
tmpmerge="$tmpdir/merge_tmp.ill"
tmpmerge_o="$tmpdir/merge_tmp_o.ill"
tmpmerge_c="$tmpdir/merge_tmp_c.ill"
tmpmerge_sd="$tmpdir/merge_tmp_sd.ill"
tmpstep="$tmpdir/sda_tmpstep.ill"
tmpda="$tmpdir/da_tmp.ill"
tmp2per="$tmpdir/2per_tmp.ill"
tmp2per_sort="$tmpdir/2per_tmp_sort.ill"
outsda="$resdir/sda.ill"
outlm83="$resdir/LM83_metrics.dat"

rm -f $tmpmerge $tmpmerge_o $tmpmerge_c $outsda $outlm83

#IFS=$'\t\n'

# Loop over each weather file...
for wea in $wealist; do
    weaname=$(basename $wea .${wea##*.})
    timestep="$weadir/${weaname}_timestep.dat"
    for pts in $ptslist; do
        ptsname=$(basename ${pts} .${pts##*.})

```

```

# Final output files..
outmerge="$resdir/${ptsname}--${weaname}--m${granularity}${rzttag}--final.ill"
echo -n "" > $outmerge
outda="$resdir/${ptsname}--${weaname}--m${granularity}${rzttag}--da.ill"
echo -n "daylight_autonomy " > $outda
outda_o="$resdir/${ptsname}--${weaname}--m${granularity}${rzttag}--da_open.ill"
echo -n "daylight_autonomy_open " > $outda_o
outda_c="$resdir/${ptsname}--${weaname}--m${granularity}${rzttag}--da_closed.ill"
echo -n "daylight_autonomy_closed " > $outda_c
outase_hours="$resdir/${ptsname}--${weaname}--m${granularity}${rzttag}--ase_hours.ill"
echo -n "" > $outase_hours
outmerge_o="$resdir/${ptsname}--${weaname}--m${granularity}${rzttag}--${bsdf_open}.ill"
echo -n "" > $outmerge_o
outmerge_c="$resdir/${ptsname}--${weaname}--m${granularity}${rzttag}--${bsdf_closed}.ill"
echo -n "" > $outmerge_c
outmerge_sd="$resdir/${ptsname}--${weaname}--m${granularity}${rzttag}--solarisc.ill"
echo -n "" > $outmerge_sd
outsched="$resdir/${ptsname}--${weaname}--m${granularity}${rzttag}--final_blinds_sched.dat"
echo "month day time $(echo $winlist |tr '\n' '|sed -e 's/.rad//g;s/ $//') > $outsched
count_line=1
while read line; do
    master_timestamp=$(echo $line |cut -d "$delimiter" -f1-3)
    echo $master_timestamp > $tmpstep
    blindsched="$ {master_timestamp} "
    echo -n "" > $tmpmerge
    echo -n "" > $tmpmerge_o
    echo -n "" > $tmpmerge_c
    echo -n "" > $tmpmerge_sd

    # Output the percent of the floor area that is in direct sunlight for each window group..
    # Find columnnumber based on timestamp.. $(cat $timestep |grep -n -e "^${master_timestamp}$" |cut -d ":" -f1)
    echo -n "" > $tmp2per
    for w in $winlist; do
        winname=$(basename $w .${w##*.})
        cat "$resdir_sd/${ptsname}--${winname}--${weaname}--m${granularity}${rzttag}.dat" |cut -d"$delimiter" -f${count_line} |tr
        '\n' "$delimiter" |sed -e "s/${delimiter}/" |awk -F"$delimiter" -v trigger=$sd_trigger -v name=$winname
        'BEGIN{count=0}{split($0,a);for(i=1;i<=NF;i++){if(a[i]>=trigger){count++}}}END{printf(name" %.2f\n",count/NF*100)}' >> $tmp2per
    done

    # Evaluate..
    cat $tmp2per |sort -rn -k 2 > $tmp2per_sort
    trig_2per=$(cat "$tmp2per" |cut -d ' ' -f2 |total |awk '{printf("%.2f", $1)}')
    sum_2per=0
    off_ttl=0
    off=""
    if [[ $(bc <<< "$trig_2per >= ${sd_trigger_per}") -eq 1 ]];then
        echo -e "$(echo $master_timestamp |tr ' ' \t) | $trig_2per% of sensors are above $sd_trigger lux, evaluating window groups." >>
$log
        while read line_2per; do
            name_2per=$(echo $line_2per |cut -d ' ' -f1)
            value_2per=$(echo $line_2per |cut -d ' ' -f2)
            sum_2per=$(echo ${sum_2per} ${value_2per} |awk '{printf("%.2f", $1+$2)}')
            sum_check=$(echo ${trig_2per} ${sum_2per} |awk '{printf("%.2f", $1-$2)}')
            echo -e "\t\t | >> $name_2per is contributing $value_2per% of the total $trig_2per% in the space, closing." >> $log
            off="$ {off} $ {name_2per}"
            off_ttl=$(echo ${off_ttl} ${value_2per} |awk '{printf("%.2f", $1+$2)}')
            if [[ $(bc <<< "$sum_check < ${sd_trigger_per}") -eq 1 ]];then
                echo -e "\t\t | >> Less than $sd_trigger_per% achieved by closing: $off (-$off_ttl%)" >> $log
                break
            fi
        done < "$tmp2per_sort"
    else
        echo -e "$(echo $master_timestamp |tr ' ' \t) | Less than $sd_trigger_per% of the analysis area is under direct sunlight:
        ${trig_2per}% " >> $log
    fi

    # Outputs..
    for w in $winlist; do
        winname=$(basename $w .${w##*.})
        if [[ $(echo $off |grep -o -e "$winname") ]];then

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```

        cut -d "${delimiter}" -f${count_line} "$resdir_dat/${ptsname}--${winname}--${bsdf_closed}--${weaname}--
m${granularity}${rzttag}.dat" |tr '\n' "${delimiter}" |sed -e "s/${delimiter}/${/s/\n/;s/^/${winname} /" >> $tmpmerge
        blindsched="${blindsched}c "
    else
        cut -d "${delimiter}" -f${count_line} "$resdir_dat/${ptsname}--${winname}--${bsdf_open}--${weaname}--
m${granularity}${rzttag}.dat" |tr '\n' "${delimiter}" |sed -e "s/${delimiter}/${/s/\n/;s/^/${winname} /" >> $tmpmerge
        blindsched="${blindsched}o "
    fi
    cut -d "${delimiter}" -f${count_line} "$resdir_dat/${ptsname}--${winname}--${bsdf_open}--${weaname}--
m${granularity}${rzttag}.dat" |tr '\n' "${delimiter}" |sed -e "s/${delimiter}/${/s/\n/;s/^/${winname} /" >> $tmpmerge_o
    cut -d "${delimiter}" -f${count_line} "$resdir_dat/${ptsname}--${winname}--${bsdf_closed}--${weaname}--
m${granularity}${rzttag}.dat" |tr '\n' "${delimiter}" |sed -e "s/${delimiter}/${/s/\n/;s/^/${winname} /" >> $tmpmerge_c
    cut -d "${delimiter}" -f${count_line} "$resdir_sd/${ptsname}--${winname}--${weaname}--m${granularity}${rzttag}.dat" |tr '\n'
"${delimiter}" |sed -e "s/${delimiter}/${/s/\n/;s/^/${winname} /" >> $tmpmerge_sd
done

# Add non-BSDF contribution..
if [ $add ];then
    cut -d "${delimiter}" -f${count_line} "$resdir_add/${ptsname}--${weaname}--m${granularity}${rzttag}.dat" |tr '\n' "${delimiter}"
|sed -e "s/${delimiter}/${/s/\n/;s/^/nonbsdf /" >> $tmpmerge
    cut -d "${delimiter}" -f${count_line} "$resdir_add/${ptsname}--${weaname}--m${granularity}${rzttag}.dat" |tr '\n' "${delimiter}"
|sed -e "s/${delimiter}/${/s/\n/;s/^/nonbsdf /" >> $tmpmerge_o
    cut -d "${delimiter}" -f${count_line} "$resdir_add/${ptsname}--${weaname}--m${granularity}${rzttag}.dat" |tr '\n' "${delimiter}"
|sed -e "s/${delimiter}/${/s/\n/;s/^/nonbsdf /" >> $tmpmerge_c
fi

echo $blindsched >> $outsched
cat $tmpmerge |cut -d "${delimiter}" -f2- |total -t" " |paste -d "${delimiter}" $tmpstep - |sed -e "s/ //" >> $outmerge
cat $tmpmerge_o |cut -d "${delimiter}" -f2- |total -t" " |paste -d "${delimiter}" $tmpstep - |sed -e "s/ //" >> $outmerge_o
cat $tmpmerge_c |cut -d "${delimiter}" -f2- |total -t" " |paste -d "${delimiter}" $tmpstep - |sed -e "s/ //" >> $outmerge_c
cat $tmpmerge_sd |cut -d "${delimiter}" -f2- |total -t" " |paste -d "${delimiter}" $tmpstep - |sed -e "s/ //" >> $outmerge_sd
((count_line++))
done < "$timestep"
echo "" >> $log

# Calculate sDA
echo "[$(date +%F-%H%M%S)] Calculating Daylight Autonomy with a threshold of ${da_trigger} lux (DA${da_trigger}): $outda" >>
$log
ncols=$((cat $tmpdir/$pts |sed -e "s/^/g/" |wc -l)+3))
for col in $(seq 4 $ncols); do
    cat $outmerge |grep -A $period_int -e "^[0-9]\{1,2\} [0-9]\{1,2\} $period_start " |sed -e "/-/d" |cut -d ' ' -f$col |awk -v
trigger=$da_trigger 'BEGIN{count=0;num=0}{if($1>=trigger){count++;num++;}END{printf("%.2f ",count/num*100)}' >> $outda
    cat $outmerge_o |grep -A $period_int -e "^[0-9]\{1,2\} [0-9]\{1,2\} $period_start " |sed -e "/-/d" |cut -d ' ' -f$col |awk -v
trigger=$da_trigger 'BEGIN{count=0;num=0}{if($1>=trigger){count++;num++;}END{printf("%.2f ",count/num*100)}' >> $outda_o
    cat $outmerge_c |grep -A $period_int -e "^[0-9]\{1,2\} [0-9]\{1,2\} $period_start " |sed -e "/-/d" |cut -d ' ' -f$col |awk -v
trigger=$da_trigger 'BEGIN{count=0;num=0}{if($1>=trigger){count++;num++;}END{printf("%.2f ",count/num*100)}' >> $outda_c
done
echo "[$(date +%F-%H%M%S)] Calculating Spatial Daylight Autonomy (DA${da_trigger}/${sda_trigger}): $outlm83" >> $log
echo -e "Calculating LM83 metrics for the \"${ptsname}\" analysis grid and \"${weaname}\" weather file." >> $outlm83
echo -e "\tSpatial Daylight Autonomy:" >> $outlm83
cat $outda |tr ' ' '\n' |awk -v trigger=$sda_trigger
'BEGIN{count=0;num=0}{if($1>=trigger){count++;num++;}END{printf("\t%.2f%s\toperated\n",count/num*100,"%")}' >> $outlm83
cat $outda_o |tr ' ' '\n' |awk -v trigger=$sda_trigger -v name=${bsdf_open}
'BEGIN{count=0;num=0}{if($1>=trigger){count++;num++;}END{printf("\t%.2f%s\tname\n",count/num*100,"%")}' >> $outlm83
cat $outda_c |tr ' ' '\n' |awk -v trigger=$sda_trigger -v name=${bsdf_closed}
'BEGIN{count=0;num=0}{if($1>=trigger){count++;num++;}END{printf("\t%.2f%s\tname\n",count/num*100,"%")}' >> $outlm83

# Calculate ASE
echo "[$(date +%F-%H%M%S)] Evaluating hours of direct exposure with a threshold of ${ase_trigger_lux} lux: $outase_hours" >>
$log
echo -n -e "\tAnnual Sunlight Exposure:" >> $outlm83
ttl_hours=$((cat $outmerge_sd |grep -A $period_int -e "^[0-9]\{1,2\} [0-9]\{1,2\} $period_start " |sed -e "/-/d" |wc -l)
ncols=$((cat $tmpdir/$pts |sed -e "/^$/d" |wc -l)+3))
for col in $(seq 4 $ncols); do
    cat $outmerge_sd |grep -A $period_int -e "^[0-9]\{1,2\} [0-9]\{1,2\} $period_start " |sed -e "/-/d" |cut -d ' ' -f$col |awk -v
trigger=$ase_trigger_lux 'BEGIN{count=0;num=0}{if($1>=trigger){count++;num++;}END{printf("%.0f ",count)}' >> $outase_hours
done
echo "[$(date +%F-%H%M%S)] Calculating Annual Sunlight Exposure (ASE${ase_trigger_lux},${ase_trigger_hours}): $outase" >> $log
cat $outase_hours |tr ' ' '\n' |awk -v trigger=$ase_trigger_hours
'BEGIN{count=0;num=0}{if($1>=trigger){count++;num++;}END{printf("%.2f%s\n",count/num*100,"%")}' >> $outlm83

```

```

done
done

echo "" >> $log
echo -e "> The results can be found in the \"\$resdir\" directory under the following naming convention:\n [pointfile]--[weatherfile]--m[N]-final.ill" >> $log
echo -e "> The blinds schedule can be found in the \"\$resdir\" directory under the following naming convention:\n [pointfile]--[weatherfile]--m[N]--final_blinds_sched.dat" >> $log
echo -e "> The Daylight Autonomy (DA$da_trigger) calculation can be found in the \"\$resdir\" directory under the following naming convention:\n [pointfile]--[weatherfile]--m[N]--da.ill" >> $log
echo -e "> The Spatial Daylight Autonomy (DA$da_trigger/$sda_trigger) calculation(s) can be found in the \"\$resdir\" directory: $outlm83" >> $log
echo "" >> $log

timeend=$(date +%F-%H%M%S)

# Calculate time elapsed..
start=$(echo $timestart |grep -e "[0-9]" |cut -d '.' -f4)
end=$(echo $timeend |grep -e "[0-9]" |cut -d '.' -f4)
start_day=$(echo $timestart |grep -e "[0-9]" |cut -d '.' -f3)
end_day=$(echo $timeend |grep -e "[0-9]" |cut -d '.' -f3)
start_mo=$(echo $timestart |grep -e "[0-9]" |cut -d '.' -f2)
end_mo=$(echo $timeend |grep -e "[0-9]" |cut -d '.' -f2)
start_yr=$(echo $timestart |grep -e "[0-9]" |cut -d '.' -f1)
end_yr=$(echo $timeend |grep -e "[0-9]" |cut -d '.' -f1)
years=$(echo $end_yr $start_yr |awk '{printf "%.4d", $1-$2}')
months=$(echo $end_mo $start_mo |awk '{printf "%.2d", $1-$2}')
days=$(echo $end_day $start_day |awk '{printf "%.2d", $1-$2}')
if [[ $(bc <<< "$end:0:2 == 24") -eq 1 ]];then
    hours=$(echo 00 ${start:0:2} |awk '{printf "%.2d", $1-$2}')
    days=$(echo $days |awk '{printf "%.2d", $1+1}')
elif [[ $(bc <<< "${start:0:2} == 24") -eq 1 ]];then
    hours=$(echo ${end:0:2} 00 |awk '{printf "%.2d", $1-$2}')
    days=$(echo $days |awk '{printf "%.2d", $1+1}')
else
    hours=$(echo ${end:0:2} ${start:0:2} |awk '{printf "%.2d", $1-$2}')
fi
minutes=$(echo ${end:2:2} ${start:2:2} |awk '{printf "%.2d", $1-$2}')
seconds=$(echo ${end:4:2} ${start:4:2} |awk '{printf "%.2d", $1-$2}')

sec="";min="";hr="";day="";
if [[ $(bc <<< "(${hours}*60+$minutes) >= 60") -eq 1 ]][[ $(bc <<< "${days} > 0") -eq 1 ]];then hr=1;elif [[ $(bc <<< "(${minutes}#-?) *60+${seconds}#-?) >=60") -eq 1 ]];then min=1;else sec=1;fi;

if [[ $sec ]];then elapsed=$(echo $days $hours $minutes $seconds |awk '{printf ($1*24*60*60+$2*60*60+$3*60+$4);printf "second(s).\n"}');fi;
if [[ $min ]];then elapsed=$(echo $days $hours $minutes $seconds |awk '{min=$1*24*60+$2*60+$3;sec=$4*1;}{if(sec < 0){min=min-1;sec=60+sec}}{printf min;printf " minutes(s) and ";printf "%.0f", sec;printf " second(s).\n"}');fi;
if [[ $hr ]];then elapsed=$(echo $days $hours $minutes $seconds |awk '{hr=$1*24+$2;min=$3*1;sec=$4*1;}{if(sec < 0){min=min-1;sec=60+sec}}{if(min < 0){hr=hr-1;min=60+min}}{printf hr;printf " hours(s), ";printf min;printf " minutes(s) and ";printf "%.0f", sec;printf " second(s).\n"}');fi;
if [[ $day ]];then elapsed=$(echo $days $hours $minutes $seconds |awk '{day=$1*1;hr=$2*1;min=$3*1;sec=$4*1;}{if(sec < 0){min=min-1;sec=60+sec}}{if(min < 0){hr=hr-1;min=60+min}}{if(hr < 0){day=day-1;hr=24+hr}}{printf day;printf " day(s), ";printf hr;printf " hours(s), ";printf min;printf " minutes(s) and ";printf "%.0f", sec;printf " second(s).\n"}');fi;

# Output time elapsed..
echo -e "> Finished in $elapsed.\n The results have been written to the ${resdir}/ directory and the log to the ${logdir}/ directory."
echo "[timeend] Finished in $elapsed" >> $log

#EOF

```


APPENDIX I: BLIND MANUFACTURER-AUTOMATED ALGORITHM A (BM-AAA) SCRIPT

The following code seen here represents the blind operation coding to simulate Blind Manufacturer-Automated Algorithm A (BM-AAA). This object is used for all the window groups on the second floor.

```
#!/bin/bash

splits="$1"
floor="$2"
if [[ ! "$3" || $(bc <<< "$3 <= 0") -eq 1 ]];then
    part=""
elif [ "$(echo $3 |grep -i -e '[a-z!@#%&^&*(,)]")" ];then
    echo ">> Error: Part specification must be a whole number."
    exit
else
    part=$3
fi

if [[ ! "$splits" || $(bc <<< "$splits <= 0") -eq 1 ]];then echo ">> Error: Number of height levels required.";exit;fi;
if [ "$(echo $splits |grep -i -e '[a-z!@#%&^&*(,)]")" ];then echo ">> Error: Number of height levels must be a whole number.";exit;fi;
if [ ! "$floor" ];then echo ">> Error: Floor not specified.";exit;fi;

period_start=9
period_end=18

weaname="USA_ID_Boise.Air.Terminal.726810_TMY3"
bsdf_open="open"
bsdf_closed="closed"
ptsname="{floor}_4x4"
granularity="4"
rhtag="--rz-35"
#email=""
email=""

# Directories
windir="/objects/windows"
ptsdir="/data"
if [ "$(ls $ptsdir)" == "" ];then ">> Error: The \"$ptsdir\" is empty.";exit 0;fi;
matdir="/materials"
if [ "$(ls $matdir)" == "" ];then ">> Error: The \"$matdir\" is empty.";exit 0;fi;
weadir="/wea"
if [ "$(ls $wadir)" == "" ];then ">> Error: The \"$weadir\" is empty.";exit 0;fi;
resdir="/results"
resdir_dat="/results/dat"
resdir_ill="/results/ill"
resdir_sd="/results/solardisc"
resdir_add="/results/add"
optdir="/options"
skydir="/skies"
tmpdir="/temp"
logdir="/log"

if [ ! -f "${ptsdir}/${ptsname}.pts" ];then echo ">> Error: ${ptsdir}/${ptsname}.pts file does not exist.";exit;fi;

mkdir -p $tmpdir $logdir

# Quantum..
input_solar="$resdir/HorizontalProfileAngle_35deg.ill"
input="$resdir/${floor}_sensors_60degrees.ill"
bt=6000
```

```

dt=500
pendepth=2.5
sh_1=3.556
sh_2=1.905

wintop=3.556
winbot=0.254
winh=$(echo "scale=5;$wintop-$winbot" |bc -l)
wini=$(echo "scale=5;$winh/$splits" |bc -l)

delimiter=" "

# Functions
function pen {
  if (( $(echo "scale=15;$solar == 0" |bc -l) ));then
    incidentangleradians="90"
    #echo "> Set to 90!"
  elif (( $(echo "scale=15;$solar <= 1" |bc -l) ));then
    incidentangleradians=$(echo "scale=15;a(sqrt((1/($solar^2))-1))" |bc -l)
    #echo "> Calculating!"
  elif (( $(echo "scale=15;$solar >= 1" |bc -l) ));then
    incidentangleradians="error"
    #echo "> >1 or <-1!"
  fi

  if (( $(echo "$incidentangleradians == 90" |bc -l) ));then
    sinincident=0
    tanincident=0
    pd=0
    pdb=0
  else
    sinincident=$(echo "scale=15;s($incidentangleradians)" |bc -l)
    tanincident=$(echo "scale=15;$sinincident/$solar" |bc -l)
    pd=$(echo "$sh_1/$tanincident" |bc -l)
    pdb=$(echo "$sh_2/$tanincident" |bc -l)
  fi
}

function sol {
  if (( $(echo "scale=15;$solar == 0" |bc -l) ));then
    horizontalprofileangle="0"
    #echo "> Set to 90!"
  elif (( $(echo "scale=15;$solar <= 90" |bc -l) ));then
    horizontalprofileangle=$(echo "scale=15;a(sqrt((1/($solar^2))-1))" |bc -l)
    #echo "> Calculating!"
  elif (( $(echo "scale=15;$solar >= 90" |bc -l) ));then
    horizontalprofileangle="error"
    #echo "> >1 or <-1!"
  fi
}

pie=$(echo "scale=20; 4*a(1)" |bc -l)
function dep {
  if (( $(echo "scale=15;$solar >= 90 || $solar <= 0" |bc -l) ));then
    pd=0
    cond=0
    tanhorizontalprofile="error [angle >= 90 || angle <= 0]"
  else
    tanhorizontalprofile=$(echo "scale=15;s(($solar*$pie/180))/c(($solar*$pie/180))" |bc -l)
    #sinincident=$(echo "scale=15;s($incidentangleradians)" |bc -l)
    #tanincident=$(echo "scale=15;$sinincident/$solar" |bc -l)
    cond="1"
    for h in $(seq 1 $splits);do
      lev=$(echo "scale=5;$wini*$h" |bc -l)
      pd=$(echo "$lev/$tanhorizontalprofile" |bc -l)
      if [[ $(bc <<< "$pd" >= $pendepth) -eq 1 ]];then break;fi;
      cond=$(echo "scale=2;1-((($h)/$splits)" |bc -l)
    done
  fi
}

#solar=0.9
#sol

```

```

#dep
#echo "$splits | $solar || pen: $pd [${lev}m, $h/$splits] | cond: $cond"
#exit
# Log
timestart=$(date +%F-%H%M%S)
if [[ "$part" ]];then
    log="$logdir/log_${part}_${timestart}.log"
else
    log="$logdir/log_${timestart}.log"
fi
echo "[${timestart}] Starting.." > $log

dir="$( cd "$( dirname "${BASH_SOURCE[0]}" )" && pwd )"
#echo -e "> Running.\n> Use the following command in a new terminal to follow the log file live:\n    tail -f ${dir}/log/$(ls ${dir}/log |tail
-1)"
echo -e "> Running.\n> Use the following command in a new terminal to follow the log file live:\n    tail -f ${dir}/log/$(basename $log)"

# Temp and material outputs..
if [[ "$part" ]];then
    dmx="/materials/inherit_dmx_${part}.rad"
    vmx="/materials/inherit_vmx_${part}.rad"
    solardisc="/materials/inherit_solardisc_${part}.rad"
    tmp_solardisc="inherit_solardisc_${part}.rad"
    tmp_additional="inherit_additional_${part}.rad"
    tmp_sky="temp_sky_${part}.rad"
    tmp_wea="temp_weather_${part}.wea"
    tmp_input="temp_input_${part}.dat"
    tmp_input_solar="temp_input_solar_${part}.dat"

    tmpmerge="$tmpdir/merge_tmp_${part}.ill"
    tmpstep="$tmpdir/sda_tmpstep_${part}.ill"
else
    dmx="/materials/inherit_dmx.rad"
    vmx="/materials/inherit_vmx.rad"
    solardisc="/materials/inherit_solardisc.rad"
    tmp_solardisc="inherit_solardisc.rad"
    tmp_additional="inherit_additional.rad"
    tmp_sky="temp_sky.rad"
    tmp_wea="temp_weather.wea"
    tmp_input="temp_input.dat"
    tmp_input_solar="temp_input_solar.dat"

    tmpmerge="$tmpdir/merge_tmp.ill"
    tmpstep="$tmpdir/sda_tmpstep.ill"
fi

scriptname=$(basename $0)

# Parse model and parameter arguments..
model=$(echo $@ |sed "s/^ *//;s/ *$//;s/\{1,\} /g;s/\{1,\}/\}/g;s/\{1,\}/-g/s/ -/t-g" |tr '\t' '\n' |grep -e "-\{1,\}i" |tail -1 |sed "s/\{1,\}i
//;s/\{1,\}/\}/;s/\{1,\}/\}/;s/\{1,\}/\}/;s/\{1,\}/\}/;s/\{1,\}/\}/")
if [ ! "$model" ];then echo -e ">> Error: Please specify the input model.";exit 0;elif [ ! -f $model ];then echo ">> Error: The specified file
does not exist.";exit 0;elif [ ! "${model##*.}" == ".rad" ];then echo -e ">> Error: The specified file is not in .rad format.";exit 0;fi;
granularity=$(echo $@ |sed "s/^ *//;s/ *$//;s/\{1,\} /g;s/\{1,\}/\}/g;s/\{1,\}/-g/s/ -/t-g" |tr '\t' '\n' |grep -e "-\{1,\}m" |tail -1 |sed "s/
-\{1,\}m //")
if [ ! "$granularity" ];then granularity=4;elif [[ $granularity == *[0-9]* ]];then if [ $granularity -gt 4 ]||[ $granularity -lt 1 ];then echo ">>
Warning: The specified granularity is out of range, using default value. [4]";granularity=4;fi;else echo ">> Warning: The specified
granularity is invalid, using default value. [4]";granularity=4;fi;
rotation=$(echo $@ |sed "s/^ *//;s/ *$//;s/\{1,\} /g;s/\{1,\}/\}/g;s/\{1,\}/-g/s/ -/t-g" |tr '\t' '\n' |grep -e "-\{1,\}rz" |tail -1 |sed "s/
-\{1,\}rz//")
if [ ! "$rotation" ];then rotation=0;rhtag="";else rhtag="--rz$rotation";fi;

# Model and materials..
modelname=$(basename $model .${model##*.})

# Lists for loops..
winlist=$(ls $windir |grep -i -e ".rad$")
ptslist=$(ls $ptsdir |grep -i -e ".pts$")
bsdflist=$(ls $matdir |grep -i -e ".xml$")
wealist=$(ls $weadir |grep -i -e ".epw$")

```

```

num_win=$(echo $winlist |tr ' ' '\n'|wc -l)
num_pts=$(cat ${ptsdir}/${ptsname}.pts |wc -l)
for i in `seq 1 ${num_win}`;do
  all_open="$ {all_open}␣"
  all_values="$ {all_values}0 "
done
for i in `seq 1 ${num_pts}`;do
  all_pts="$ {all_pts}0 "
done
all_open=$(echo $ {all_open} |sed -e "s/ $//")
all_values=$(echo $ {all_values} |sed -e "s/ $//")

nwg=$(cat $input |head -1 |sed -e "s/ $//" |tr ' ' '\n'|wc -l |awk '{print $1-3}')

if [[ "$part" ]];then
  tail -n+4 $input |sed -e "s/-nan/0/g;s/nan/0/g" |grep -A 0 -e "^${part} " |sed -e "/-/d" > $tmpdir/$tmp_input
  tail -n+2 $input_solar |sed -e "s/-nan/0/g;s/nan/0/g" |grep -A 0 -e "^${part} " |sed -e "/-/d" > $tmpdir/$tmp_input_solar
else
  tail -n+4 $input |sed -e "s/-nan/0/g;s/nan/0/g" > $tmpdir/$tmp_input
  tail -n+2 $input_solar |sed -e "s/-nan/0/g;s/nan/0/g" > $tmpdir/$tmp_input_solar
fi

header=$(head -1 $input |cut -d ' ' -f4- |sed -e "s/ $//")
header_solar=$(head -1 $input_solar |sed -e "s/ $//")

x_header=$(cat ./data/${floor}_4x4.pts |cut -d ' ' -f1 |tr '\n' ' ' |sed -e "s/$\n;/s/ $//")
y_header=$(cat ./data/${floor}_4x4.pts |cut -d ' ' -f2 |tr '\n' ' ' |sed -e "s/$\n;/s/ $//")

# Final output files..
if [[ "$part" ]];then
  outmerge="$resdir/${ptsname}--${weaname}--m${granularity} ${rzttag}--custom_${part}.ill"
  outsched="$resdir/${ptsname}--${weaname}--m${granularity} ${rzttag}--final_blinds_sched_${part}.dat"
else
  outmerge="$resdir/${ptsname}--${weaname}--m${granularity} ${rzttag}--custom.ill"
  outsched="$resdir/${ptsname}--${weaname}--m${granularity} ${rzttag}--final_blinds_sched.dat"
fi

echo " $x_header" > $outmerge
echo " $y_header" >> $outmerge
#echo "month day time $(echo $winlist |tr '\n' ' ' |sed -e "s/.rad//g;s/ $//")" > $outsched
echo "month day time $(echo $header |tr '\n' ' ' |sed -e "s/^ //;s/ $//")" > $outsched

err_count=0
o_count=0
c_count=0
m_count=0

if [[ "$part" ]];then
  first_line=$(grep -in -e "^1 1 1 " $input |cut -d ":" -f1)
  count_line=$(grep -in -e "^${part} 1 1 " $input |sed -e "/-/d" |cut -d ":" -f1 |awk -v fl=$first_line '{print $1-fl+1}')
else
  count_line=1
fi

while read line; do
  hour=$(echo $line |cut -d "$delimiter" -f3)
  master_timestamp=$(echo $line |cut -d "$delimiter" -f1-3)
  ts=$(echo ${master_timestamp} |awk '{printf("% .2d/% .2d % .2d%s", $1,$2,$3,":00")}')
  echo $master_timestamp > $tmpstep
  blindsched="$ {master_timestamp} "
  echo -n "" > $tmpmerge
  condition=""
  wg_count=4

  #if [[ $(echo $header_solar |cut -d ' ' -f4- |grep -i -e "e" ) ]];then
  solar_o=$(echo $header_solar |tr ' ' '\n'|grep -ni -e "e" |cut -d ':' -f1)
  solar=$(head -$ {count_line} $tmpdir/$tmp_input_solar |tail -1 |cut -d ' ' -f${solar_o})
  #sol
  dep

```

```

pd_e=$pd
cond_e=$cond
#elif [[ $(echo $header_solar |cut -d' ' -f4- |grep -i -e "n" ) ]];then
solar_o=$(echo $header_solar |tr '\n' |grep -ni -e "n" |cut -d':' -f1)
solar=$(head -${count_line} $tmpdir/$tmp_input_solar |tail -1 |cut -d' ' -f${solar_o})
#sol
dep
pd_n=$pd
cond_n=$cond
#elif [[ $(echo $header_solar |cut -d' ' -f4- |grep -i -e "s" ) ]];then
solar_o=$(echo $header_solar |tr '\n' |grep -ni -e "s" |cut -d':' -f1)
solar=$(head -${count_line} $tmpdir/$tmp_input_solar |tail -1 |cut -d' ' -f${solar_o})
#sol
dep
pd_s=$pd
cond_s=$cond
#elif [[ $(echo $header_solar |cut -d' ' -f4- |grep -i -e "w" ) ]];then
solar_o=$(echo $header_solar |tr '\n' |grep -ni -e "w" |cut -d':' -f1)
solar=$(head -${count_line} $tmpdir/$tmp_input_solar |tail -1 |cut -d' ' -f${solar_o})
#sol
dep
pd_w=$pd
cond_w=$cond
#fi

if [[ $(bc <<< "${hour} >= ${period_start}") -eq 1 ]] && [[ $(bc <<< "${hour} <= ${period_end}") -eq 1 ]];then
for wg in $header; do
winname=$(echo $wg |sed -e "s/^[0-9]*/")
#winnam=$(basename $win) .${win##*.})
win_o=$(echo $winname |sed -e "s/./_/g;s/_/./g" |rev |cut -d'_' -f1)
##solar_o=$(echo $header_solar |tr '\n' |grep -ni -e "${win_o}" |cut -d':' -f1)
# BSDF switch for North facade...
if [[ $(echo $win_o |grep -i -e "n") ]];then bsdf_closed="closed_5";else bsdf_closed="closed_1";fi;

if [[ $(echo $win_o |grep -i -e "e") ]];then
pd=$pd_e
cond=$cond_e
elif [[ $(echo $win_o |grep -i -e "n") ]];then
pd=$pd_n
cond=$cond_n
elif [[ $(echo $win_o |grep -i -e "s") ]];then
pd=$pd_s
cond=$cond_s
elif [[ $(echo $win_o |grep -i -e "w") ]];then
pd=$pd_w
cond=$cond_w
fi
wg_position=$((

##solar=$(head -${count_line} $tmpdir/$tmp_input_solar |tail -1 |cut -d' ' -f${solar_o})
#echo -e "\n$winname\nsolar: $solar\nsolar_o: $solar_o"
##pen
#echo -e "\n$winname\nsolar (solar)"
#lux=$(tail -n+4 $input_sens |cut -d" " -f${wg_count} |head -${count_line} |tail -1)
lux=$(echo $line |cut -d' ' -f${wg_count} |head -${count_line} |tail -1)
if [[ $(bc <<< "${lux} >= ${bt}") -eq 1 ]];then
# Close 100%
cat "$sresdir_dat/${ptsname}--${winname}.1--${bsdf_closed}--${weaname}--
m${granularity}${rhtag}.dat" |sed -e "/^0$/d" |cut -d"${delimiter}" -f${count_line} |tr '\n' "${delimiter}" |sed -e
"s/${delimiter}$/,s/\n/:s/^\n/" >> $tmpmerge
cat "$sresdir_dat/${ptsname}--${winname}.2--${bsdf_closed}--${weaname}--
m${granularity}${rhtag}.dat" |sed -e "/^0$/d" |cut -d"${delimiter}" -f${count_line} |tr '\n' "${delimiter}" |sed -e
"s/${delimiter}$/,s/\n/:s/^\n/" >> $tmpmerge
condition=${condition}
blindsched=${blindsched}1 "
((c_count++))
elif [[ $(bc <<< "${lux} < ${dt}") -eq 1 ]];then
# Open 100%

```

```

        cat "$sresdir_dat/${ptsname}--${winname}.1--${bsdf_open}--${weaname}--
m${granularity}${rzttag}.dat" |sed -e "/^0$/d" |cut -d"$delimiter" -f${count_line} |tr '\n' "$delimiter" |sed -e
"s/${delimiter}$//;s/$\n/;/s/^/${winname} /" >> $tmpmerge
        cat "$sresdir_dat/${ptsname}--${winname}.2--${bsdf_open}--${weaname}--
m${granularity}${rzttag}.dat" |sed -e "/^0$/d" |cut -d"$delimiter" -f${count_line} |tr '\n' "$delimiter" |sed -e
"s/${delimiter}$//;s/$\n/;/s/^/${winname} /" >> $tmpmerge
        condition="${condition}███"
        blindsched="${blindsched}0 "
        ((o_count++))
    else
        # Intermittent condition...
        cat "$sresdir_dat/${ptsname}--${winname}.1--${bsdf_closed}--${weaname}--
m${granularity}${rzttag}.dat" |sed -e "/^0$/d" |cut -d"$delimiter" -f${count_line} |tr '\n' "$delimiter" |sed -e
"s/${delimiter}$//;s/$\n/;/s/^/${winname} /" >> $tmpmerge
        cat "$sresdir_dat/${ptsname}--${winname}.2--${bsdf_open}--${weaname}--
m${granularity}${rzttag}.dat" |sed -e "/^0$/d" |cut -d"$delimiter" -f${count_line} |tr '\n' "$delimiter" |sed -e
"s/${delimiter}$//;s/$\n/;/s/^/${winname} /" >> $tmpmerge
        condition="${condition}███"
        blindsched="${blindsched}${cond} "
        ((m_count++))
    fi

#
# Quantum logic before we move down to O/I/C decision...
# ████████

#if [ "$(echo $line |cut -d' ' -f${wg_count})" == "o" ];then
# Open
#cut -d "$delimiter" -f${count_line} "$sresdir_dat/${ptsname}--${winname}--${bsdf_open}--${weaname}--
m${granularity}${rzttag}.dat" |tr '\n' "$delimiter" |sed -e "s/${delimiter}$//;s/$\n/;/s/^/${winname} /" >> $tmpmerge
#cut -d "$delimiter" -f${count_line} "$sresdir_dat/${ptsname}--${winname}--${weaname}--m${granularity}${rzttag}.dat" |tr
'\n' "$delimiter" |sed -e "s/${delimiter}$//;s/$\n/;/s/^/${winname} /" >> $tmpmerge
#((o_count++))
#condition="${condition}███"
#elif [ "$(echo $line |cut -d' ' -f${wg_count})" == "c" ];then
# Closed
#cut -d "$delimiter" -f${count_line} "$sresdir_dat/${ptsname}--${winname}--${bsdf_closed}--${weaname}--
m${granularity}${rzttag}.dat" |tr '\n' "$delimiter" |sed -e "s/${delimiter}$//;s/$\n/;/s/^/${winname} /" >> $tmpmerge
#echo "${winname}" >> $tmpmerge
#((c_count++))
#condition="${condition}███"
#else
#((err_count++))
#condition="${condition}E "
#fi
((wg_count++))
per=$(echo $wg_count $nwg |awk '{printf("%1f",($1-4)/$2*100)}')
echo -ne "\e[0K\r> ${ts} [${per}%]"
done
cat $tmpmerge |cut -d "$delimiter" -f2- |total -t" |paste -d "$delimiter" $tmpstep - |sed -e "s/ $/" >> $outmerge
#((count_line++))
echo -e "${ts}\t$(echo ${condition} |sed -e 's/ $/')" >> $log
else
condition=${all_open}
blindsched="${blindsched}${all_values} "
#echo -e "$(echo $master_timestamp |tr ' ' '\t')\t | >> Out of operable range, opening all." >> $log
echo ${all_pts} |paste -d "$delimiter" $tmpstep - |sed -e "s/ $/" >> $outmerge
#((count_line++))
echo -e "${ts}\t${condition}" >> $log
echo -ne "\e[0K\r> ${ts} [OOR]"
fi
echo $blindsched |sed -e 's/ $/' >> $outsched
((count_line++))
done < "$tmpdir/$tmp_input"
timeend=$(date +%F-%H%M%S)
echo -e "\e[0K\r> Blind operation finished. [Timeend]\n"
echo -e "> Errors..\t${err_count}\n> Open...\t${so_count}\n> Closed..\t${c_count}\n> Other..\t${m_count}"
echo "[Timeend] Finished." >> $log
echo -e "" >> $log
echo -e "Errors..\t${err_count}\nOpen...\t${so_count}\nClosed..\t${c_count}\nOther..\t${m_count}" >> $log

```

```

if [[ "$part" ]];then
    result="$resdir/floor--final.ill"
    schedule="$resdir/floor--schedule.ill"
    echo -n "" > $result
    echo -n "" > $schedule
    for i in $(seq 1 12); do
        if [[ $i -eq 1 ]];then
            #cat $resdir/$(ls $resdir |grep -i -e "--final_blinds_sched_$.dat$") |tail -1 >> $result
            cat $resdir/$(ls $resdir |grep -i -e "--custom_$.ill$") >> $result
            cat $resdir/$(ls $resdir |grep -i -e "--final_blinds_sched_$.dat$") >> $schedule
        else
            tail -n+3 $resdir/$(ls $resdir |grep -i -e "--custom_$.ill$") >> $result
            tail -n+2 $resdir/$(ls $resdir |grep -i -e "--final_blinds_sched_$.dat$") >> $schedule
        fi
    done
# Calculate time elapsed..
start=$(echo $timestart |grep -e "[0-9]" |cut -d '.' -f4)
end=$(echo $timeend |grep -e "[0-9]" |cut -d '.' -f4)
start_day=$(echo $timestart |grep -e "[0-9]" |cut -d '.' -f3)
end_day=$(echo $timeend |grep -e "[0-9]" |cut -d '.' -f3)
start_mo=$(echo $timestart |grep -e "[0-9]" |cut -d '.' -f2)
end_mo=$(echo $timeend |grep -e "[0-9]" |cut -d '.' -f2)
start_yr=$(echo $timestart |grep -e "[0-9]" |cut -d '.' -f1)
end_yr=$(echo $timeend |grep -e "[0-9]" |cut -d '.' -f1)
years=$(echo $end_yr $start_yr |awk '{printf "%.4d", $1-$2}')
months=$(echo $end_mo $start_mo |awk '{printf "%.2d", $1-$2}')
days=$(echo $end_day $start_day |awk '{printf "%.2d", $1-$2}')
if [[ $(bc <<< "$end:0:2 == 24") -eq 1 ]];then
    hours=$(echo 00 ${start:0:2} |awk '{printf "%.2d", $1-$2}')
    days=$(echo $days |awk '{printf "%.2d", $1+1}')
elif [[ $(bc <<< "$start:0:2 == 24") -eq 1 ]];then
    hours=$(echo ${end:0:2} 00 |awk '{printf "%.2d", $1-$2}')
    days=$(echo $days |awk '{printf "%.2d", $1+1}')
else
    hours=$(echo ${end:0:2} ${start:0:2} |awk '{printf "%.2d", $1-$2}')
fi
minutes=$(echo ${end:2:2} ${start:2:2} |awk '{printf "%.2d", $1-$2}')
seconds=$(echo ${end:4:2} ${start:4:2} |awk '{printf "%.2d", $1-$2}')

sec="" ;min="" ;hr="" ;day="";
if [[ $(bc <<< "${hours}*60+$minutes) >= 60") -eq 1 ]][[ $(bc <<< "${days} > 0") -eq 1 ]];then hr=1;elif [[ $(bc <<< "${minutes#-
?}*60+${seconds#-?}) >=60") -eq 1 ]];then min=1;else sec=1;fi;
if [[ $sec ]];then elapsed=$(echo $days $hours $minutes $seconds |awk '{printf ($1*24*60*60+$2*60*60+$3*60+$4);printf "
second(s).\n"}');fi;
if [[ $min ]];then elapsed=$(echo $days $hours $minutes $seconds |awk '{min=$1*24*60+$2*60+$3;sec=$4*1;}{if(sec < 0){min=min-
1;sec=60+sec;}}{printf min;printf " minutes(s) and ";printf "%.0f", sec;printf " second(s).\n"}');fi;
if [[ $hr ]];then elapsed=$(echo $days $hours $minutes $seconds |awk '{hr=$1*24+$2;min=$3*1;sec=$4*1;}{if(sec < 0){min=min-
1;sec=60+sec;}{if(min < 0){hr=hr-1;min=60+min;}}{printf hr;printf " hours(s), ";printf min;printf " minutes(s) and ";printf "%.0f",
sec;printf " second(s).\n"}');fi;
if [[ $day ]];then elapsed=$(echo $days $hours $minutes $seconds |awk '{day=$1*1;hr=$2*1;min=$3*1;sec=$4*1;}{if(sec < 0){min=min-
1;sec=60+sec;}{if(min < 0){hr=hr-1;min=60+min;}{if(hr < 0){day=day-1;hr=24+hr;}}{printf day;printf " day(s), ";printf hr;printf "
hours(s), ";printf min;printf " minutes(s) and ";printf "%.0f", sec;printf " second(s).\n"}');fi;

# Output time elapsed..
echo -e "> Finished in $elapsed.\n The results have been written to the ${resdir}/ directory and the log to the ${logdir}/ directory."
echo "[${timeend}] Finished in $elapsed" >> $log

if [ ${email} ];then
    #sendmail_err=$(sendmail -d0.4 -bv root |head -1 |grep -ie 'version')
    echo -ne "> Sending notification to ${email}..."
    timeend_time=$(echo $timeend |cut -d '.' -f4)
sendmail ${email} <<EOF
subject: [LM-83] Blind operation completed.
from: IDL-LM83-Script
The "${ptsname}--${weaname}--m${granularity}${rzttag}--custom.ill" run finished at ${timeend_time:0:2}:${timeend_time:2:2} on $(echo
$timeend |cut -d '.' -f2)/$(echo $timeend |cut -d '.' -f3)/$(echo $timeend |cut -d '.' -f1).
Duration: ${elapsed}
Best regards,
LM83

```

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EOF

APPENDIX J: BLIND MANUFACTURER-AUTOMATED ALGORITHM B (BM-AAB) SAMPLE INPUT FILE

The following code applies to only one window group on the North-east façade. The algorithm represented by the EnergyManagementSystem:Program object in EnergyPlus, contains the code for a blind control response. The code seen here is identical for all the window groups but uses different exterior vertical illuminance values through an external CSV file includes the vertical exterior illuminance values obtained from the daylighting engine RADIANCE.

```

EnergyManagementSystem:ProgramCallingManager,
  Window Shading Device EMS Controller2301, !- Name
  BeginTimestepBeforePredictor, !- EnergyPlus Model Calling Point
  Set_Shade_Control_State2301; !- Program Name 1

EnergyManagementSystem:Actuator,
  Sub_Surface_zn_ne_04_e_Shading_Deploy_Status, !- Name
  zn_ne_04_e, !- Actuated Component Unique Name
  Window Shading Control, !- Actuated Component Type
  Control Status; !- Actuated Component Control Type

EnergyManagementSystem:TrendVariable,
  SPT2301, !- Name
  Shade_Position2301, !- EMS Variable Name
  1; !- Number of Timesteps to be Logged

EnergyManagementSystem:Sensor,
  Shade_Position2301, !- Name
  EMS, !- Output:Variable or Output:Meter Index Key Name
  Erl Shading Control Status2301; !- Output:Variable or Output:Meter Name

! CONTROL ALGORITHMS
EnergyManagementSystem:Program,
  Set_Shade_Control_State2301; !- Name
  Set SPT_Value = @TrendValue SPT2301 1, !- Program Line 1
  IF Sensor12 < 15000, !- Program Line 2
    Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Off,
    ELSEIF Sensor12 > 15000 && Sensor12 < 35000 && SPT_Value == 0,
    Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Off,
    ELSEIF Sensor12 > 35000 && HPA3 < 26,
  Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A4
  ELSEIF Sensor12 > 15000 && Sensor12 < 35000 && SPT_Value > 0 && HPA3 < 26,
  Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_On, !- A4
  ELSEIF Sensor12 > 35000 && HPA3 > 44,
  Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Off,
  ELSEIF Sensor12 > 15000 && Sensor12 < 35000 && SPT_Value > 0 && HPA3 > 44,
  Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Off,
  ELSEIF Sensor12 > 35000 && HPA3 > 26 && HPA3 < 44,
  Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_middle, !- A8
  ELSEIF Sensor12 > 15000 && Sensor12 < 35000 && SPT_Value > 0 && HPA3 > 26 && HPA3 < 44,
  Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Interior_Blind_middle, !- A8
  ELSE, !- A9

```

```
Set Sub_Surface_zn_ne_04_e_Shading_Deploy_Status = Shade_Status_Off, !- A10
ENDIF;          !- A11
```

```
EnergyManagementSystem:OutputVariable,
Erl Shading Control Status2301, !- Name
Sub_Surface_zn_ne_04_e_Shading_Deploy_Status, !- EMS Variable Name
Averaged,          !- Type of Data in Variable
ZoneTimeStep;     !- Update Frequency
```

```
EnergyManagementSystem:ProgramCallingManager,
Init Window Shading Device Control Constants2301, !- Name
BeginNewEnvironment, !- EnergyPlus Model Calling Point
InitializeShadeControlFlags2301; !- Program Name 1
```

```
EnergyManagementSystem:Program,
InitializeShadeControlFlags2301, !- Name
Set Shade_Status_Interior_Blind_middle = 3.0, !- Program Line 1
Set Shade_Status_Off = 0.0, !- Program Line 2
Set Shade_Status_Interior_Blind_On = 6.0; !- <none>
```

```
EnergyManagementSystem:GlobalVariable,
Shade_Status_Interior_Blind_middle; !- Erl Variable 1 Name
```

```
EnergyManagementSystem:GlobalVariable,
Shade_Status_Off; !- Erl Variable 1 Name
```

```
EnergyManagementSystem:GlobalVariable,
Shade_Status_Interior_Blind_On; !- Erl Variable 1 Name
```