RESEARCH

EVALUATING GLARE IN LEED CERTIFIED BUILDINGS TO INFORM CRITERIA FOR DAYLIGHTING CREDITS

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ABSTRACT

Extensive documentation has been developed to support the benefits of daylight for building occupants. Recently, the high performance building industry has shown a trend towards prioritizing better daylighting conditions. In response to this trend, the Leadership in Energy and Environmental Design (LEED) rating system now addresses daylighting and views as one of the criteria for compliance. However, effective daylighting has its challenges—most importantly addressing the issue of glare. This paper discusses the issue of glare and its relationship with requirements for effective daylighting within the criteria of the LEED rating system. In this study, a LEED certified building on Montana State University's campus was considered as a case study. This paper conducts an analysis by comparing the results obtained from compliance procedures for LEED with independent evaluations of glare using simulation and post occupancy evaluation surveys. This paper concludes that the 'illuminance simulation' option provided in the current version of LEED (LEED v4) for compliance does not adequately address the issue of glare. This paper provides recommendations to improve the LEED rating system for indoor environmental quality which include: the incorporation of glare assessment in the evaluation procedures of daylighting and views; the use of dynamic simulations that incorporate climatic conditions in the evaluation of daylighting; and evaluating glare in early stages of design by using simulation tools.

KEYWORDS

daylighting, glare, green building rating system

I. INTRODUCTION

a. Daylighting in Buildings

Natural light is highly desirable in the design and construction of high performance buildings, as it contributes to the health and happiness of occupants and decreases the need for supplemental electric lighting [1]. These potential benefits have made daylight optimization an increasingly important design parameter in new environmentally sustainable buildings [2, 3]. Designing buildings which prioritize daylight, however, is a complex process that can negatively impact

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other aspects of indoor environmental quality such as acoustics, thermal comfort and visual comfort [4]. This paper considers effective daylighting to be in terms of daylight sufficiency, visual comfort and available views.

b. Visual Comfort and Glare

Visual comfort of building occupants can be adversely affected by a glare, and glare can result from poor lighting conditions in general. This paper focuses on direct glare from daylighting. Glare is defined by human perception and therefore its definition varies by source. The IESNA's Lighting Handbook defines glare as the sensation produced by luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted to cause annoyance, discomfort or loss in visual performance. [5]. Several other publications have addressed various aspects of glare in terms of acceptable luminance levels and ratios, contrast and types of sources [6, 7, 8]. Sources of glare can include direct sunlight, reflective surfaces, artificial lights, and screens, depending on background illuminance, occupant position, viewing angle, and sun angle. [7].

Disability glare is a type of glare that reduces an occupant's visual performance and impedes normal visual tasks. Discomfort glare on the other hand is a more subjective and qualitative sensation, making it difficult to understand and hard to rate in a consistent or useful way [9]. It is noted that the discomfort of direct glare stems from two facts: first, the eye adapts (rapidly) to the average brightness of the overall visual scene; and second, the eye is attracted to the highest luminance in that scene. [7]. This paper will be focusing on discomfort glare because provisions for discomfort glare in daylighting design are often overlooked.

c. Evaluating Glare

In more than 80 years of research into glare, several attempts have been made to reduce discomfort glare to a single standard quantitative metric [9]. Several metrics are currently in use to measure discomfort glare. Calculations for glare incorporate physical quantities such as: the luminance of the glare source; the solid angle subtended by the source; the angular displacement of the source from the observer's line of sight; and the general field of luminance controlling for the adaptation levels of the observer's eye (background luminance) [10]. Several attempts have been made by various experimental studies to quantify the magnitude of discomfort from glare, integrating the impact of the above-mentioned physical quantities. In each of these previous studies, a glare index was calculated with an equation that modifies the relationships between the basic parameters in order to predict glare as accurately as possible based on controlled laboratory tests. Existing metrics for quantifying glare include: the Building Research Station Glare Equation (BRS or BGI), Cornell Equation or Daylight Glare Index (DGI), CIE Glare Index (CGI), Unified Glare Rating (UGR), and Daylight Glare Probability (DGP). A detailed discussion of these metrics can be found in several publications [3, 11, 12, 13].

Daylight Glare Probability (DGP) is a glare metric that was developed by Jan Wienold and Jens Christoffersen at the Fraunhofer Institute for Solar Energy Systems and the Danish Building Research Institute, respectively, and first published in 2006 in Energy and Buildings [10]. DGP assesses the probability that an occupant will be disturbed by glare conditions, using the vertical eye illuminance of an entire scene and its relationship to specific potential glare sources within that scene [10].

DGP is calculated using the following equation:

$$DGP = 5.87 \times 10^{-5} E_v + 0.0918 \times \log_{10}\left(1 + \sum_{i=1}^{n} \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{1.87} p_i^2}\right) + 0.16$$

Where E_v is the vertical eye illuminance (lux), L_s is the luminance of the source (cd/m^2), ω is the solid angle of the source, and p is the position index.

DGP was developed based on controlled tests of two identical sidelit office spaces, one containing a human occupant, the other capturing HDR images at the same location and angle as the occupant. DGP was the first glare prediction model that was based on studies of physical daylit spaces as opposed to computer simulations, which contributes to its reliability as a glare evaluation metric [14]. DGP uses both areas of bright luminance and the total vertical eye illuminance for a viewing angle of the subject in order to account for both the factors causing discomfort. In addition, the utilization of vertical eye illuminance, Ev, is an input that allows this method to predict discomfort without the presence of a significant contrast [15]. When compared to existing glare metrics, with its emphasis on the probability of the person being disturbed instead of the magnitude of the glare source, DGP has a strong correlation with the user's response regarding glare perception.

DGP can be evaluated using a computer-based open source software 'Evalglare', developed by Jan Wienold at the Fraunhofer Institute for Solar Energy Systems [16]. The software can be used to evaluate the potential for glare from digital images in either HDR format that are generated from digital images subjected to various exposure settings generated by a digital camera and HDR software; or a PIC format that can be created from a Radiance simulation [16]. When assessing the digital images, Evalglare uses various algorithms to calculate the luminance value and location of each pixel of the image. The program then uses this information to calculate the values such as background mean luminance, glare source luminance, glare source position, solid angle of glare sources, vertical illuminance, and direct vertical illuminance, etc., which contribute to evaluating the potential of glare [17].

The use of DGP has been supported by several studies that have assessed different aspects of glare such as situations of excessive light and luminance ratios, occupant position and adaptability, window and spatial geometries, and exterior daylight conditions. Jakubiec and Reinhart conclude that DGP is the preferred glare metric for different daylighting conditions and spaces, doing the best job handling high contrast situations and producing results that fall within the high and low bounds of other metrics [3]; Carlucci et al. conclude that the DGP is the most appropriate of all current glare metrics to address absolute glare issues because the method of calculating DGP is highly correlated with users response to glare perception, [12]; Van Den Wymelenberg et al. performed a study involving HDR imaging and a survey to investigate details as the appropriate luminance threshold selection and the correlation of observations to DGP and DGI and confirmed the consistent performance of DGP over DGI [18]. In a later study evaluating daylighting conditions by adjusting motorized window shadings, Van Den Wymelenberg and Inanici conclude that the use of DGP exhibits stronger correlation than DGI when comparing measured versus simulated data, however the authors also noted that simpler illuminance based metrics such as vertical illuminance provided better predictions of glare [19]; Suk and Schiler conducted experiments that compared Radiance simulations with measurements of glare in order to validate simulated DGP [17]. The study proved that the software was valuable in validating the individual indices across a range of situations.

This paper focuses on DGP as the best option available for measuring glare, while understanding that it is complex and its parameters must be dealt with carefully. The results of the study presented in this paper utilize the provisions for Evalglare in the DIVA for Rhino [16, 20] software to conduct the analysis.

d. Provisions in Green Rating Systems for Indoor Environmental Quality

In the United States, Leadership in Energy and Environmental Design (LEED) from the United States Green Building Council (USGBC), advocates daylighting of buildings and views to the exterior from living and working spaces [21]. LEED criteria strongly encourage building envelope designs that maximize access to daylight and views, often in opposition with other indoor environmental quality factors such as thermal comfort, acoustic privacy, and visual comfort. In addition to providing acceptable ranges for daylighting metrics, LEED provides tools encouraging designers to improve their projects through design iteration and evaluation. This paper addresses the issue of visual comfort and its relationship with the provisions for daylighting in the LEED v4 standards for Indoor Environmental Quality.

LEED v4 for New Construction (NC) offers three compliance paths for daylighting, two of which are simulation options, and the third measurement-based. Credit for the measurement option cannot be achieved until the building is built and occupied. Daylight simulations can be used in the design process, enabling designers to evaluate options through iteration.

The first simulation option gauges the Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) of spaces to demonstrate compliance. sDA describes the percentage of building floor area that receives at least a designated minimum amount of daylight illuminance over the course of all occupied hours in a year. This is a newly introduced option in LEED v4 and is dependent on weather data as well as occupant schedule. ASE describes the floor area that receives a designated amount of direct sunlight, identifying overlit areas and potential sources of glare. Using option one, LEED v4 requires daylight autonomy (illumination levels of 300 lux for at least 50% of occupied hours in a year) in 55% of regularly occupied floor area to be considered adequately daylit. LEED awards an additional point to those buildings which achieve daylight autonomy across 75% of floor area [21]. Finally, the credit requires that the 1000 lux direct-sunlight limit is not exceeded for more than 250 hours a year for more than 10% of a space, equating to a maximum ASE of 10%.

The second compliance option under LEED v4 uses point-in-time workplane illuminance calculations, limiting acceptable values to between 300 lux and 3000 lux. This option is similar to the primary daylight compliance path for LEED v3 2009. For either compliance option, glare control devices such as roller shades are required for all exterior glazing unless proven unnecessary through compliance with the IES LM-83-12 document published by IES and referenced in LEED v4 [22]. As compared to option two, the ASE / sDA method is considered a more holistic and accurate method for daylight analysis [23].

e. Addressing Glare in LEED

The transition from LEED v2009 to LEED v4 has set more stringent limits on illuminance levels in regularly occupied spaces, attempting to focus on the most appropriate light levels for human activity. The LEED v4 rating system prevents most disability glare in new construction by setting an upper limit on illuminance levels within its criteria for Daylight. Discomfort glare on the other hand, which is the focus of this study, can occur under less extreme illuminance conditions, which means it can still be a problem within the bounds of LEED-acceptable illuminance. While the changes in LEED v4 prevent more cases of disability glare, the impact of this change on controlling discomfort glare is less thoroughly understood. Furthermore, LEED daylight compliance is based on horizontal illuminance calculations, a metric which does not adequately predict discomfort glare [14]. Perhaps due to the lack of a universally applicable rating system for glare potential, many designers ignore the phenomenon of discomfort glare altogether [3, 24]. Consistent with this issue, the LEED v4 rating system mentions glare and suggests that its mitigation is imperative, but does not define the term "glare" itself or distinguish between disability and discomfort glare [21].

The introduction of sDA and ASE in the LEED v4 NC IEQ Daylight Credit is a step toward avoiding potential glare in new construction. Setting an upper limit on direct sun exposure at the workplane avoids the possibility of most glare produced by reflections on horizontal work surfaces. The requirement for glare control devices on all exterior glazing is well-justified, as many unpredictable factors and occupant preferences come into play when buildings are occupied. However, Foster and Oreszczyn [25] showed that occupants tend to leave shades down in a glare-preventing position more often than necessary, which decreases potential for daylight and views.

II. RESTATING THE CURRENT ISSUE & GOALS OF RESEARCH

It is apparent from the amount of existing research in the field of daylight glare that this phenomenon affects the indoor environmental quality of green buildings [23, 24, 26, 27]. Unfortunately, due to a lack of consensus and robust documentation around discomfort glare and its design implications, the issue can easily go unaddressed and unnoticed until a building is occupied. LEED standards have recently made progress towards addressing glare by introducing annual daylight metrics which identify overlit spaces. However, certain standards within LEED v4 still rely heavily on glare control devices, allowing occupants to control their environment but also negating some potential for daylight and views [25].

Glare is intrinsically connected with daylighting and views. Hence, these terms should be understood in the context of one another. The goal of this study is to test whether the use of a standardized glare metric such as Daylight Glare Probability would improve LEED criteria for daylight and views, leading to better building design and higher standards for environmental performance in new construction.

III. METHODOLOGY

a. Work Flow

To accomplish the goals of this research, a study of a LEED v3 certified building on the Montana State University campus was undertaken, comparing daylight illuminance calculations and annual daylight metrics for LEED v2009 and v4 against a quantitative glare analysis of selected spaces in the building and an independent POE questionnaire distributed to faculty and staff.

b. Assessing the Performance of a LEED Certified Building—Jabs Hall Montana State University

Jabs Hall is located at the Montana State University (MSU) campus in Bozeman, Montana, USA (45.67° N, 111.05° W). The 50,830 ft^2, four-story building is home to MSU's Jake Jabs College of Business, and is comprised of private offices, open/shared offices, conference rooms, collaborative work spaces, south-facing classrooms, a small café, and a large, central, two-story atrium space. Jabs Hall was certified LEED Gold under v2009 New Construction (LEED v3). The building also passed Indoor Environmental Quality standards for both Daylight and Views, receiving one LEED point for each [28].

Since Jabs Hall first opened in May of 2015, complaints from professors and students have arisen in regards to extensive south-facing glazing that lacks sufficient shading. It is common knowledge to those using Jabs Hall that glare in classrooms is a problem, leading to overheating, a visual nuisance, and the over-use of shading devices, which decrease daylight and the potential for views. These complaints are strongest in the winter months when sun angles are low, the ground is often covered in snow, and the building is most often occupied. This study uses Jabs Hall as a test case for understanding the relationship between daylight, views, glare, and occupant satisfaction in the context of LEED v4 criteria for Indoor Environmental Quality.

c. LEED Point-in-time Illuminance Analysis

The Integrated Design Lab at Montana State University received digital models of Jabs Hall from the project architects for performing a LEED IEQ analysis for daylight and views. The building was initially assessed using criteria provided in LEED v3. For the purpose of this research, the building was reassessed using criteria provided in LEED v4, which can be found in the LEED v4 user manual [21].

Digital models were reduced to their essential elements and imported to AGi32, a daylight calculation software from Lighting Analysts [29]. Illuminance values were then calculated on a 2.5 foot square grid, 2.5 feet above the finish floor, across the entirety of each regularly occupied space.

As recommended in the LEED manual, simulations were performed for September 21st at 9 AM and 3 PM with clear sky conditions in Bozeman, Montana (45.5° N, 111° W) using the CIE clear sky model. The surface conditions and material reflectance used in AGi32 are listed in Table 1. Using a spreadsheet, illuminance grid calculations from 9 AM and 3 PM were overlaid to understand which points were within the acceptable illuminance range for both times.

TABLE 1. User Defined Material Properties Implemented in AGi32 Simulation [5].

OBJECT	REFLECTANCES
Ceilings	80%
Walls	50%
Floor	30%
Ground	20%
Mullions	80%
Roof	70%
Exterior Glazing	70% Visual Transmittance

d. As-Built Analysis

Room Selection

The analysis presented here focuses on classroom spaces in Jabs Hall. Classrooms comprise a large percentage of building floor area. They are clustered along the building's south façade; have the highest concentration of glazing to wall ratio in the building; and were the source of most of the building's complaints regarding glare. Limiting the study to one classroom space per floor provided a manageable dataset with known glare potential. Building plans with selected spaces are presented in Figure 1.

Software

For the purpose of this study, 3D CAD drawings of Jabs Hall were updated and edited to match as-built conditions including furniture layouts and accurate reflectance values of materials. Material reflectance values were measured and calculated using a Konica Minolta LS-100 Luminance Meter and a standard Kodak 18% Reflectance Gray Card.

3D CAD drawings of selected spaces were imported to Rhinoceros 5.0 (Rhino), a 3D modeling program with extensive plugin capabilities [30]. These virtual spaces were evaluated using DIVA 4.0, a plugin which uses the Radiance rendering engine and Evalglare program to analyze spaces for daylight and glare properties [16, 20]. Custom Radiance materials were created in the DIVA program to match measured conditions as accurately as possible. A TMY3 weather file for Bozeman, MT–Gallatin Field was used in all simulations [31]. Each model included a ground plane at the accepted standard reflectance of 20%, and surrounding buildings were modeled where relevant.

Radiance is a physically-based rendering program capable of simulating complex geometries with flexible reflection and transmittance material properties using a backward raytracing algorithm. Radiance also has the ability to model specular components [32]. The program has been extensively validated and has been found to reliably model interior illuminances for a wide range of measured sky conditions [33, 34, 35]. However, other studies have also concluded the need to correctly model external ground and obstruction reflectances as well as use of sky models can significantly impact simulation accuracy [36, 37].

Simulation Setup

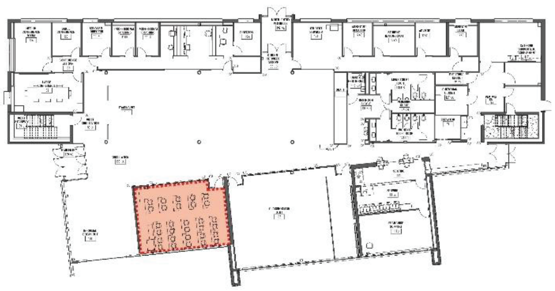
For each space that was analyzed in Jabs Hall, a single camera view was set in Rhino based on an understanding of space use derived from furniture layouts and discussions with occupants. For example, in classrooms, the camera view represents the point of view of the instructor. The point of view of the student was omitted to limit the scope of this study. Camera views set in DIVA were used to produce HDR images at selected points in time, which are composed of spot illuminance readings for every pixel in the image. DIVA then utilizes the Evalglare program developed by Jan Wienold to determine potential glare sources and calculate a numeric Daylight Glare Probability rating [16].

Point-in-Time and Annual Glare Simulations

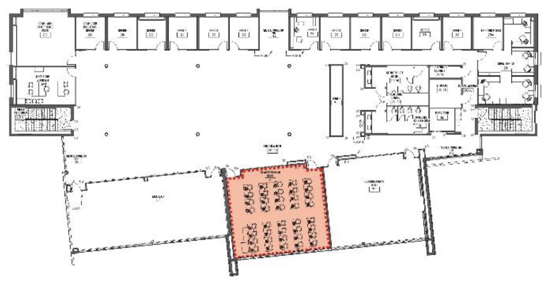
To keep results relevant to the scope of this study, point-in-time glare simulations were performed for September 21st at 9 AM and 3 PM with clear sky conditions: the required condition and times for LEED daylight illuminance calculation option. The simulation produces a marked scene and a single number for DGP. This single number is then rated on a scale of acceptability, which is provided in Table 2.

FIGURE 1. Building Plans.

Perspective Rendering of Jabs Hall



First floor plan, Room 103



Second floor plan, Room 211

Third floor plan, Room 307

Fourth floor plan, Room 415

Note: Selected classrooms on each floor are marked with a box.

September 21 at 9 AM and 3 PM is a narrow scope of daylight and glare potential. In order to understand how this date would relate to year-round building occupancy, annual glare graphs were generated using DIVA. The annual glare graphs present a potential for glare in the space selected using TMY3 weather data for the entire year and a selected schedule of occupancy. These simulations indicate glare ratings for every hour of the year on color-coded graphs correlated to daylight glare probability ratings listed in Table 2.

sDA & ASE Calculations

The same DIVA models used to simulate glare were also used to calculate Spatial Daylight Autonomy (sDA) and Annual Sun Exposure (ASE). Based on requirements of the IES LM-83-12 document referenced in LEED v4, calculation grids were placed 30 inches above the finish floor, with nodes spaced 24 inches apart. In all four classrooms, 100% of exterior glazing faces the same direction, 6 degrees east of south. Standard LEED-compliant glare-control devices

TABLE 2. Glare Perception Ranges [3].

DGP RANGE	PERCEPTION OF GLARE	P.O.E DESIGNATION
DGP < 35%	Imperceptible	Gloomy, Dim, Comfortable
35% < DGP < 40%	Perceptible	Bright
40% < DGP < 45%	Disturbing	Glary
DGP > 45%	Intolerable	

were implemented in the models for all exterior glazing. Building occupancy schedule was set to the standard 8am to 6pm with Daylight Savings Time, both satisfying LEED criteria and aligning with the actual building schedule.

For each classroom, DIVA was used to produce a percentage of floor area with at least 50% Daylight Autonomy over the course of a year, as well as a percentage of floor area receiving at least 1000 lux for more than 250 hours in a year. LEED v4 awards points to buildings which attain at least 55% sDA, and not more than 10% ASE; buildings with an sDA result of at least 75% receive an additional point. DIVA also calculates a percentage of hours during which shades are open.

d. Post Occupancy Evaluation (POE) Questionnaire

To obtain a more accurate picture of the occupant satisfaction in Jabs Hall, a web-based, post-occupancy evaluation (POE) questionnaire was developed in Qualtrics [38] and was distributed to building occupants at the beginning of the Fall '16 semester (September 2016). The responses were collected after a period of one month. This tool was used to clarify the specific nature and location of the glare problem. The questionnaire focused on staff and faculty that work in the building and required the participants to evaluate their overall satisfaction with the daylighting conditions based on their experience of occupying the spaces over a period of spring, summer and fall semesters. Of the 48 faculty members included in this survey, 38 faculty members responded in regard to use of classroom spaces.

The survey gathered building use patterns, and perceptions of indoor environmental quality from the occupants. The specific questions and structure were based on a standard form from UC Berkeley's Center for Built Environment [39]. The questionnaire has been implemented in numerous studies to evaluate the relationship between IEQ and occupant satisfaction [40]. Questions about daylighting required participants to input their perceptions of daylighting quality in the spaces that they typically occupy. The participants were provided with different qualities describing daylighting conditions in their spaces, including gloomy, dim, comfortable, bright and glary. When assessing occupant perception, these qualities were translated to the glare ratings of intolerable, disturbing, perceptible or imperceptible as seen in Table 2. The correlations between DGP ranges and discomfort classification were adopted from a study assessing discomfort glare by Jakubiec and Reinhart [3]. The participants were then asked to document how they perceived the quality of these spaces at different times of day. A representative questionnaire is provided in Table 3 below. Details of this survey can be found in the report on evaluating comfort levels of building occupants in Jabs Hall on Montana State University campus [41].

TABLE 3. Sample Questions and Answers from the POE.

QUESTIONS

- **Which term best describes the lighting conditions in room most of the time?**
  - Gloomy
  - Dim
  - Comfortable
  - Bright
  - Glary
  - Other
- **Please rate your overall experiences with regards to lighting.**

	Extremely satisfied	Somewhat satisfied	Neither satisfied nor dissatisfied	Somewhat dissatisfied	Extremely dissatified	N/A
Overall impression of lighting in classroom spaces	☐	☐	☐	☐	☐	☐

- **Do you ever experience distracting or uncomfortable glare when working in Jabs Hall?**
  - Yes
  - No
- **Do you have to adapt your seating position while at work to avoid glare?**
  - Not applicable
  - No
  - Yes, 25% of the time
  - Yes, 50% of the time
  - Yes, 75% of the time
  - Yes, all the time

Results were collected for all classrooms on all four floors. Results were then consolidated for each floor and finally for the entire building with the purpose to detect any discrepancies in responses regarding visual comfort on different scales of assessment. Results from specific classrooms were then correlated to glare simulations.

In addition to questions about daylighting and views, the survey specifically asked whether participants ever experience disturbing or distracting glare from sunlight while using the building. A positive answer to this question directed participants to a series of follow-up questions about the type, intensity and consequences of that glare. In this manner, survey responses were sorted by whether they indicated a glare issue, where in the building glare is experienced, and by characteristics of that glare. Glare responses were then compared with the amount of daylighting in the space.

V. RESULTS

a. LEED Compliance Results to Obtain Daylighting Credits

Using the criteria outlined in LEED v4 for the illuminance simulation option (option 2), the building failed with 70% of floor area within the acceptable range. In order to achieve one LEED v4 point for Daylight, 75% of the floor area must be within the acceptable range. The results take into account the performance of regularly occupied spaces in the entire building. However, on closer examination of the results, the building failed because of insufficient lighting (i.e., levels below 300 lux) versus the spaces being over lit (i.e., levels above 3000 lux). When considering the LEED compliance for Views, the building passes with 90% of floor area contributing to quality views.

Therefore, this paper focuses on south-facing classrooms where insufficient lighting is not an issue. Large glazing area in these spaces contributed to the compliance for both daylight and views. However, areas of high illuminance due to low sun angles and glazing area pose issues for glare. When accounted for individually for compliance, all four classrooms were within the acceptable illuminance range for LEED v4 Option 2 Daylight compliance. As seen from Table 4, all the rooms are compliant with LEED v4 criteria.

b. Annual Daylight Analysis

The results take into account the performance of four south facing classrooms that were selected by this study. Using the criteria outlined in LEED v4 for the spatial daylight autonomy option (option 1), all four rooms failed. On closer examination of the results, the classrooms failed because of too much direct sunlight, with rooms reporting ASE within a range of 47.2%–82.5%. On the other hand, for three of the four rooms, sDA values were within the acceptable range. Results are presented in Table 5 below.

TABLE 4. Point-in-time Daylight Analysis for Selected Rooms.

Room Number	% Floor Area in Acceptable Range
103	86.8
211	89.6
307	80.0
415	77.7

TABLE 5. Annual Daylight Analysis for Selected Rooms.

Room Number	sDA	ASE	% Time Shades Open
103	99.4	63.9	70
211	52.4	47.2	58
307	56.5	52.1	57
415	96.8	82.5	57

c. Point-in-time and Annual Glare Analysis

The point-in-time and annual glare results are presented in Figures 2 and 3. Point-in-time glare simulations provide glare sources for each scene. It is apparent from simulations that reflective surfaces such as mullions on southern fenestration are liable to produce glare (Refer to Figure 2 and Figure 3). In addition, sunlight falling directly on walls and desks can produce glare. Direct sunlight and ambient sky brightness are also sources of glare in scenes where the camera (occupant) is facing towards the sun. Exterior surface reflections also contribute to glare. Specific material reflectance can affect the probability of glare. For example, in room 415 at 3 PM, the far wall (50% reflective) is producing reflected glare while the near desks (55% reflective) were not. When compared with the annual glare graphs, the point-in-time glare ratings insufficiently represent the full range of glare conditions, and therefore may be misleading in understanding annual glare potential.

In the analysis, a trend was observed towards higher glare potential on upper floors over lower floors. Surrounding buildings block direct sunlight on the lower floors, decreasing the potential for glare. However, glare potential is also dependent upon direction of the occupant and time of day, as can be seen comparing room 211 where the instructor faces east and room 307 where the instructor faces west.

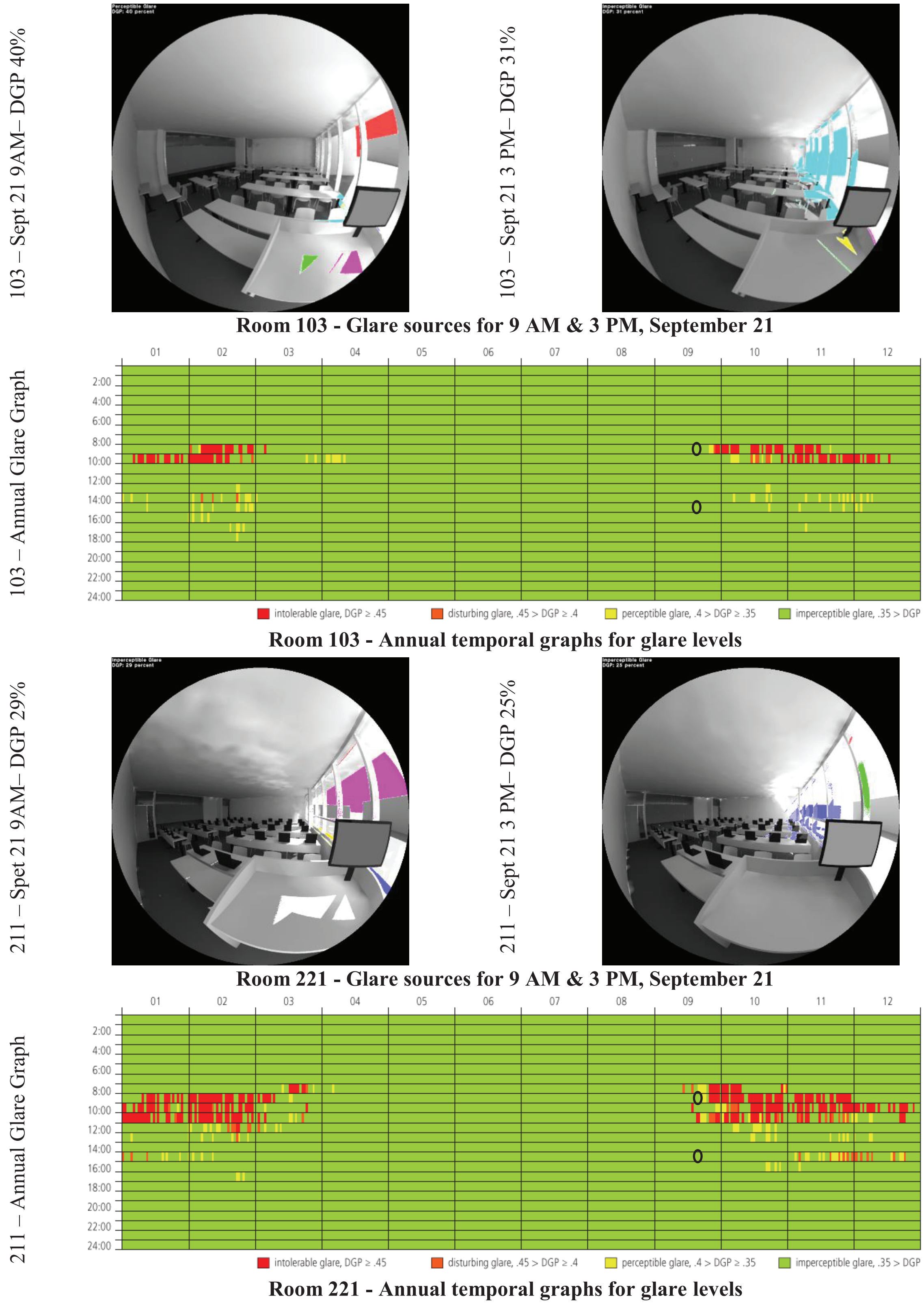
d. POE Survey Assessments

Survey participants were asked whether at any time they experienced glare in Jabs Hall, and if so how it affected their use of the spaces they regularly occupied. Results show that: 41% (n = 16) of the participants answered that they experienced glare at some point in time; 14% (n = 5) of the participants had issues with face to face contact due to glare; 23% (n = 9) adapted their work positions due to glare; 7% (n = 3) felt uncomfortable when adapting due to glare; and 23% (n = 9) of participants answered that specific conditions worsened glare. The conditions cited for exacerbation of glare included weather conditions (such as cloud coverage and snow), sun angles, and specific space uses such as video conferencing.

Survey participants were asked which term from a given list best described lighting conditions experienced in the room "most of the time." The analysis was narrowed to focus on classrooms. Figure 4 compares the number of responses at each time of day from each specific classroom, classrooms on each floor, classrooms in general, and the overall building. Responses indicating "other" were inconsistent in their reasoning and were not considered in conclusions presented here.

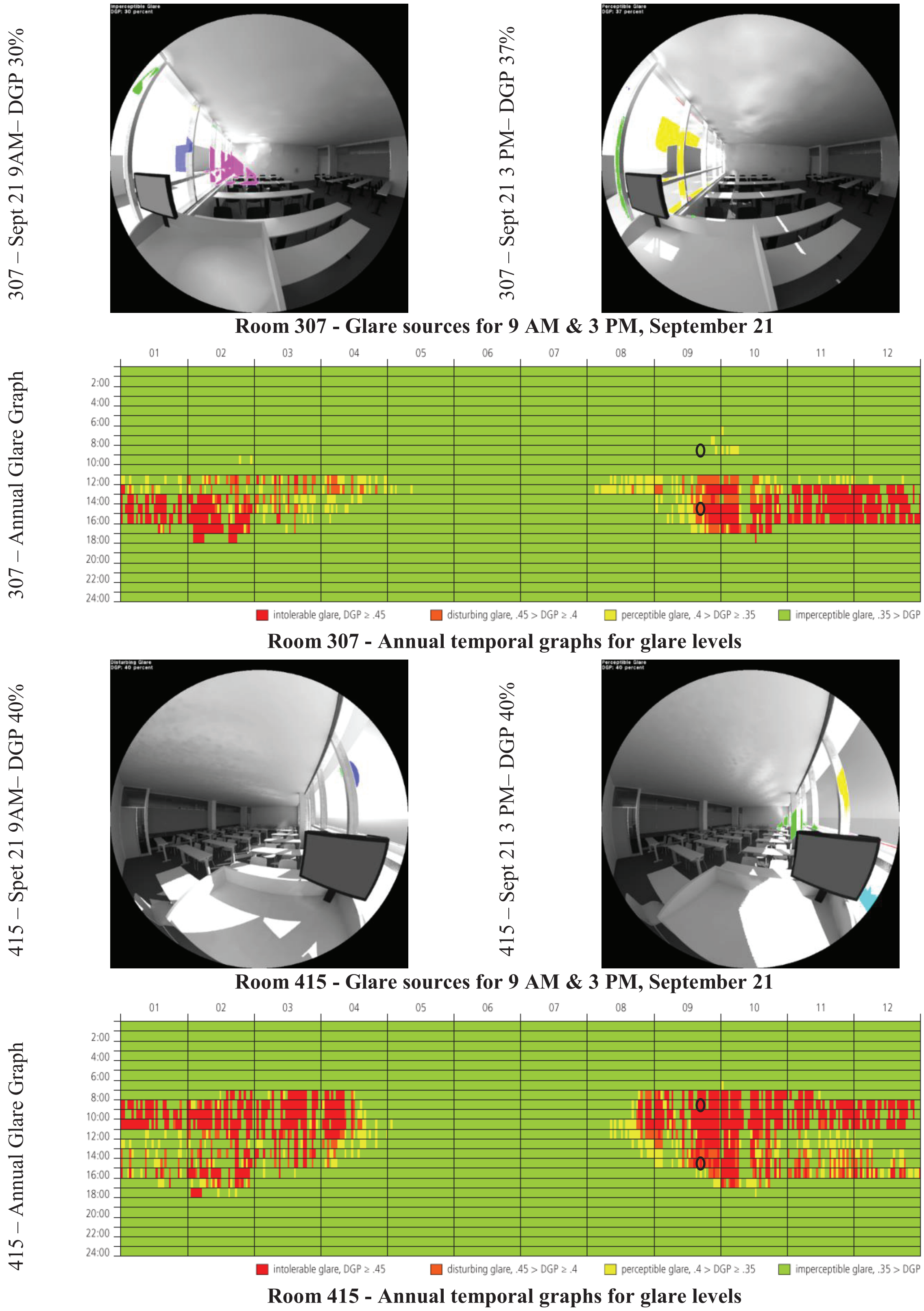
When considering the results for the entire building, which includes the performance of classrooms, offices and collaborative spaces, 53% (n = 20) of the responses selected comfortable conditions and 21% (n = 8) of the responses selected either bright or glary conditions. When considering the performance of classroom spaces alone, 56% (n = 21) of participants felt comfortable while 30% (n = 11) of participants felt that the conditions were either bright or glary. When considering the daylighting conditions for classrooms per floor, it was observed that participants were more comfortable on lower floors (i.e., 68% selected comfortable, n = 26) than on the upper floors (51% selected comfortable conditions, n = 19). Similar patterns of visual comfort conditions were observed in the classrooms selected on each floor. Based on the data set, correlations between time of day and responses indicating glare were inconclusive.

FIGURE 2. Point-in-time Glare Analysis for Rooms 103 and 211.



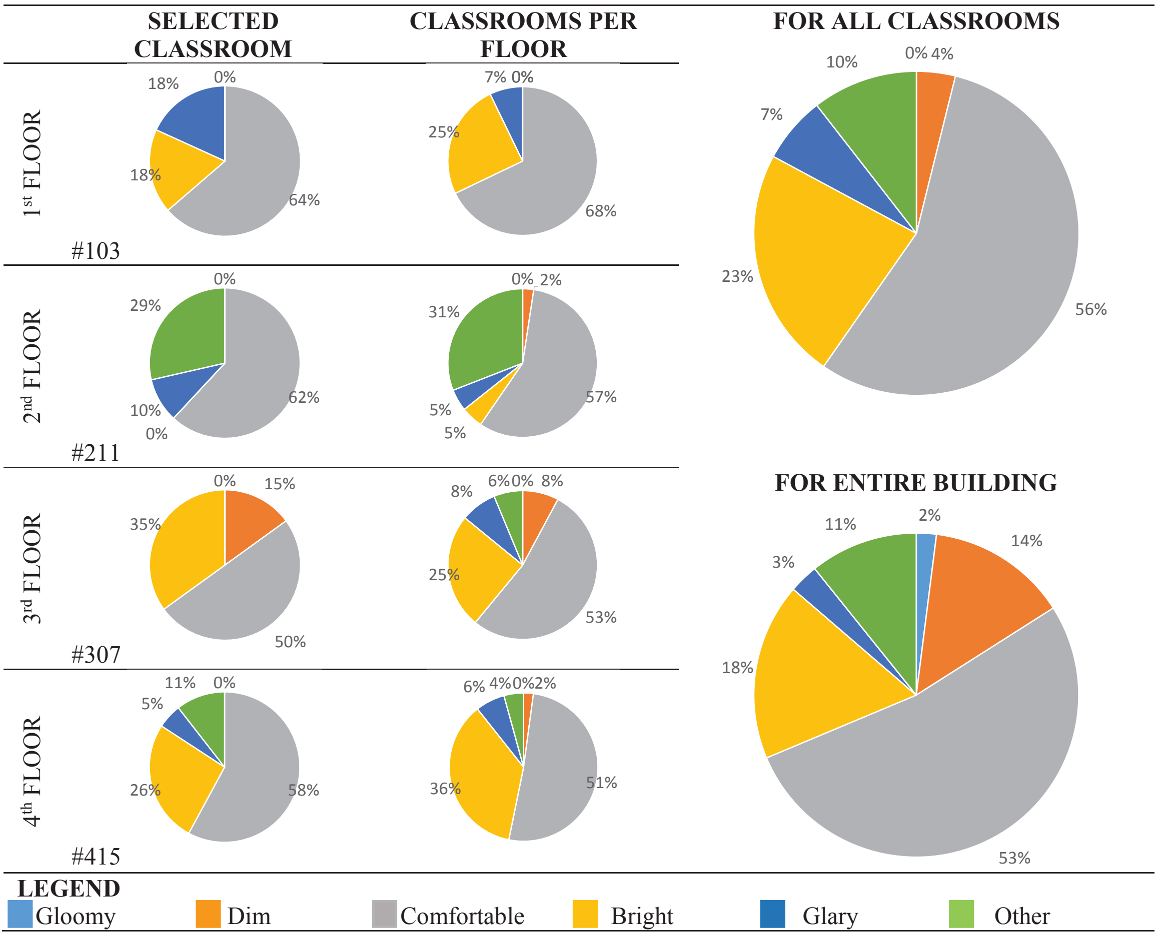
Note: Glare conditions at 9:00AMand 3:00 PM on 21st September are marked with ovals

FIGURE 3. Point-in-time Glare Analysis for Rooms 307 and 415.



Note: Glare conditions at 9:00AMand 3:00 PM on 21st September are marked with ovals

FIGURE 4. Results of P.O.E Survey for Classrooms & Entire Building.



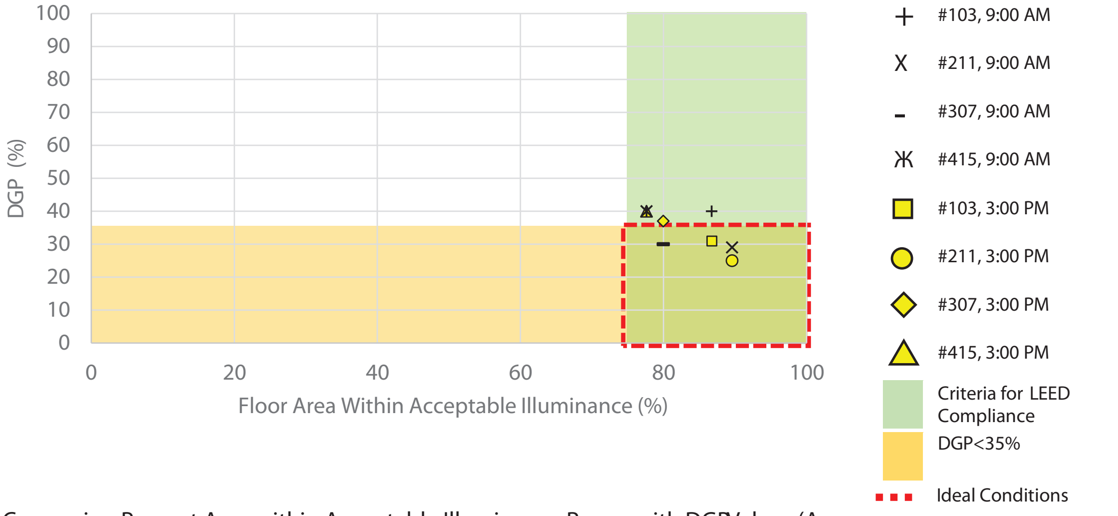
e. Comparing results from LEED, point-in-time glare results and POE survey for the four selected rooms

In its final step, the study compared the point-in-time illuminance calculations, point-in-time glare results, and POE assessments for the four selected classrooms. This step reported the percentage of space that obtained illuminance values within the range acceptable by LEED v4. Point-in-time glare results were reported in terms of DGP and then translated to a corresponding perception of glare as noted in Table 2. POE assessments were reported in terms of percentage of participants who felt comfortable in the selected space, as well as percentage of occupants who experienced bright and glary conditions. Scatterplots of results are presented in Figure 5. LEED v4 compliance criteria for acceptable illuminance range and glare perception ranges are superimposed on these graphs.

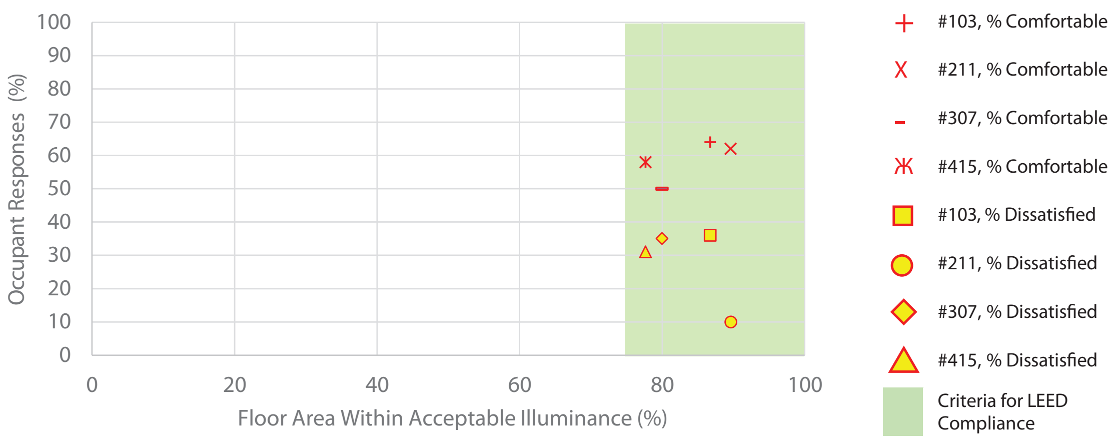
In Figure 5A, the overlap of desirable ranges for DGP simulation results and LEED illuminance can be seen in the lower right. For 21st of September, while all points fall within the acceptable range of floor area meeting illuminance requirements (i.e. 75% of floor area between 300 and 3,000 lux), four of the eight points indicate potential for glare.

The majority of occupants reported to be "comfortable" in classroom spaces as seen from the POE. A strong correlation between POE response, glare, and illuminance simulation is not

FIGURE 5. Comparing Percent Area within Acceptable Illuminance Range with DGP and Occupant Response.



a) Comparing Percent Area within Acceptable Illuminance Range with DGP Values (As obtained from point-in-time simulation for 21st September)



b) Comparing Percent Area within Acceptable Illuminance Range with Occupant Response from P.O.E.

observed due to the small sample size used in this analysis. However, there were a significant number of responses indicating "bright" or "glary" conditions when illuminance values were measured as being well within the acceptable range for LEED compliance (Figure 5B) which is comparable to the results from DGP simulation as reported in Section d of the Results.

VI. CONCLUSIONS AND RECOMMENDATIONS

Based on the observations from the literature review and results, this study concludes that incorporating glare analysis into LEED's evaluation of daylighting and quality views could improve the indoor environmental design of future buildings. Although LEED v4 for indoor environmental quality requires all regularly occupied spaces to implement glare control devices, the POE survey indicates that issues from glare still occur. In the case of Jabs Hall, glare control devices are found in all classrooms yet roughly 30% of the POE respondents experienced bright or glary conditions. The study recommends a more elaborate description of shading devices and high-dynamic-range imaging sensor operated controls with manual overrides to be included in the LEED requirements for glare mitigation. The appropriate use and control of shades to mitigate glare has to be demonstrated by means of simulation.

It is also important to note that glare control devices such as roller shades decrease potential for both daylight and quality views by their very nature of covering windows if not controlled appropriately. Certain programs such as DIVA that are used to simulate ASE also provide a metric to account for the percentage of occupied hours when the shades are open. This could be a helpful metric for both development of LEED in understanding glare control and for designers attempting to affectively implement interior shades or blinds.

Glare needs to be dealt with in earlier stages of design, as it is often overlooked through current LEED criteria for daylight and quality views analysis. Strategies such as: orientation; room dimensions; interior design; surface finishes; glazing type; position and size of fenestration systems; and design of facades play important roles in improving daylighting and views conditions and mitigating glare. It is recommended that the LEED rating criteria acknowledge these design decisions and encourage appropriate application by establishing appropriate design guidelines [42]. It is also recommended for LEED to require designers to demonstrate the validity of their proposed design decisions over a corresponding base-case by means of simulations.

While glare, daylight and views are all important factors for indoor environmental quality, they have competing criteria for design. Increasing fenestration area, for example, will generally improve views and allow more daylight, while also increasing glare potential. These three factors must be considered simultaneously to avoid compromise. As demonstrated by this study, the extensive use of glazing on the south façade of Jabs Hall contributes significantly to occupant views with over 75% of the building spaces and over 90% of classroom spaces providing views, but stops short in providing adequate visual comfort to the occupants in these spaces. Introducing an established glare evaluating metric such as the DGP in addition to the illuminance level calculations, into the LEED criteria for indoor environmental quality would be a step towards addressing this issue.

As seen in the background section of this study (Evaluating glare), glare is dependent on both horizontal and vertical illuminance values. As a supplement to horizontal illuminance values at the work plane, LEED may need to consider the perspective view of typical occupant positions that have been identified in the building seeking compliance, and their respective vertical illuminance values.

Use of weather data for simulations is encouraged, as climate conditions and sky cover vary for different locations. As reported in the study, LEED v4 has taken steps in that direction with the incorporation of sDA and ASE metrics under simulation option 1. Evaluating the performance of the four classrooms in Jabs Hall using the sDA and ASE metrics indicated that the rooms are severely overlit. With its dependence on point-in-time evaluation, the illuminance simulation option is inadequate to fully understand daylight and glare. As demonstrated by comparing point-in-time and annual glare assessments by this study, looking only at two hours during a single day is not an accurate representation of daylighting or glare conditions throughout a year. Evaluating the performance of the four rooms using point-in-time analysis did not identify the issue with glare reported by the occupants in the POE and confirmed by the glare assessment conducted by this study. Therefore, Option 2 provided in LEED v4 is not sufficient for detecting issues of glare, especially regarding low sun angles at higher latitudes. The study recommends the use of annual glare assessment in addition to daylight autonomy analysis, which makes use of annual weather file for the location.

While the introduction of annual daylight evaluation indices such as ASE and sDA by LEED v4 is a step towards identifying adequate daylighting conditions and potential for glare, these indices cannot identify instances where glare is a result of reflective surfaces. To evaluate the potential of glare from such surfaces, it is recommended to incorporate results from appropriate glare metrics such as DGP in early design stages when designers are involved in the selection of appropriate materials as well as in the LEED criteria for daylight compliance. Criteria such as that used in Table 2 of this paper can be utilized to evaluate the space for potential glare. In order to include evaluation of glare in the illuminance simulation option to obtain LEED daylight credits, several issues have to be addressed which include selection of representative rooms, camera location for scene evaluations, and points-in-time glare evaluations. Rooms considered for glare analysis should be regularly occupied spaces that are representative of activities, spatial layout and orientation within the building. Selecting appropriate location of cameras for scene evaluations in the representative room depends on the activities in the room and sight lines of occupants. When considering a timeframe for glare evaluation, the selection of point-in-time method by this study was found to be insufficient because of its inability to evaluate the potential of glare under different conditions. An annual glare evaluation that utilizes weather data should be performed prior to the point-in-time evaluation method as it takes into account the variations in occupancy and sky conditions. The resulting graph could be used to identify and select problem conditions for further evaluation using point-in-time glare metrics.

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