Daylighting Performance in Schools between Simulation Predictions and Field Verifications

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Abstract

Design simulations and building performance predictions create challenges to building designers when attempting to prove these expectations in buildings post occupancy. This paper investigates two main research questions: (1) what are the discrepancies and where do they lie between daylighting performance simulation predictions and actual daylighting performance in schools; and (2) what are the factors that cause these discrepancies? — in order to develop a factor of reality (FR) to bridge gaps between design predictions and actual performance of buildings. To answer these questions, the study compares the results of daylighting design simulation predictions with post-occupancy assessments of four south-facing classrooms —with different daylighting systems— in an elementary school in Eugene, OR (ASHRAE CZ 4c).

Daylight and visual comfort metrics are analyzed for these classrooms through a critical examination of simulation results and field measurements. Results show that while static daylighting metrics were consistently lower in actual classrooms than what was predicted in simulations, dynamic metrics were higher in actual classrooms. Interestingly, classrooms with dual daylighting systems (such as side and top daylighting) show lower degrees of discrepancies between simulation and actual measurements. Conclusions are reported as a conceptual framework for future daylighting design and simulations of K-12 schools that achieve both dynamic daylighting metrics and enhanced occupants' comfort. Future studies should investigate these discrepancies and incorporate a Factor of Reality (FR) to provide better accuracy in future daylighting simulations.

Introduction

To achieve an effective daylighting design, current dynamic daylighting metrics stress the need to provide uniform daylight distribution and to limit excessive illumination levels (IESLM-83-12, IES RP-5-13). While the application of these metrics is important for visually-critical spaces, current best practices in K-12 school daylighting design face challenges in achieving these metrics and maintaining occupant's satisfaction, simultaneously (Elzeyadi, 2018). These challenges are partly related to classrooms requiring a balance between achieving dynamic daylighting metrics and the management of glare for both the teacher and the students

to provide an engaging learning environment. In addition, other behavioral issues related to changes in wall displays and media projections can alter Light Reflectance Values (LRV) of the classrooms.

Generally, classroom daylighting design needs to support a wide range of visual tasks that often require different levels of illumination and glare control. The issue is magnified in the way occupants use classrooms. Student and teachers have different view-sheds, in opposite directions, and at different heights that will require variations in brightness patterns to accommodate both perspectives. By employing daylighting simulation software based on the Radiance engine, most of these parameters can be tested to predict daylighting performance during early design phases of a project. But no matter how advanced the software is, without detailed comparisons between how daylighting metrics are simulated in relation to how actual daylit classroom spaces perform, we will continue to face gaps between design assumptions and actual space performance. An important objective of this study is to address this gap by examining different factors and assumptions in school daylighting simulations.

One of the main factors influencing daylighting design in schools is the need to provide sufficient illumination levels required for a multifunctioning environment and accommodates different technological advancements in teaching (Wu & Ng, 2003). One of the studies that considered these different modes (Drosou, Haines, Mardaljevic, & Brembilla, 2016) concluded that occupants extensively used video display terminal (VDT) equipment and electric lights during teaching hours. Further, they found that once blinds were closed, they were likely to stay in that position until custodial staff opened them. This highlights the need for incorporating these behavioral patterns in simulation models to improve daylight performance predictions. In addition to these patterns, other factors like the presence and location of furniture as well as seasonal variations to trees could affect predicted outcomes (Drosou, Brembilla, & Mardaljevic, 2016). Although the incorporation of these variables in daylight simulation might be challenging, it is an important step that could bridge the gap between simulation predictions and post-occupancy performance (Li, Lau, & Lam, 2004).

Despite the relatively large number of studies that investigated glare metrics, their use and applicability are still limited. In a study that examined the consistency among different glare metrics, Suk & Schiler (2013) found differences in the estimated glare that spanned from imperceptible to intolerable in some cases. Further, differences were found between simulated and measured glare indices that often influenced the glare classification level. Suk & Schiller speculated that differences between measured and simulated glare levels could be due to the fact that simulated high dynamic range images (HDRIs) have a much greater range of luminance values, compared to ranges of HDRIs taken using digital cameras.

Recent studies revealed substantive bias due to anchor and order effects of glare metrics primarily at lower glare criteria and stressed the for caution when interpreting subjective evaluations of discomfort due to glare between measured and computed scenes (Kent, Fotios & Altomonte, 2018). Another study by Bian & Ma (2018) found a high agreement between simulated and measured Daylight Glare Probability (DGP) values only but not other metrics. Overall, it is suggested that there might be other variables that influence the level of accuracy in predicting daylighting glare in the built environment. Furthermore, it can be concluded that there is a lack of studies on daylighting in schools, particularly, to address occupant's visual comfort under different learning modes.

Research questions

Findings of previous studies investigating the actual performance of school classroom spaces are not always conclusive of a positive and clear correlation between daylighting levels in these environments and student comfort (Elzeyadi, 2013). This is in part due to excessive glare and poor lighting distribution in these spaces, which were designed to meet certain daylighting metrics that do not account for visual comfort (Elzeyadi, 2017). For instance, dynamic daylighting metrics (IES LM-83-12 2012) recommend that a minimum 55% of the spatial daylit area >300 lux be achieved for 50% of the occupied time (sDA300 50%). Recent studies suggested that adopting dynamic daylighting metrics such as the Annual Sunlight Exposure metric (ASE) might lead to dull and monotonous spaces (Reinhart, 2015).

In another study, more than 55% of the occupants in The New York Times building, which was designed to manage glare and reduce sunlight penetration, felt that the daylighting system did not impact their satisfaction positively (Lee et. al., 2013). In addition to these variables, glare perception in relation to daylight apertures in classrooms combined with a lack of controllability is a pressing problem (Winterbottom & Wilkins, 2009).

Based on previous observations, the specific question of this paper is: How do the results of detailed daylight classrooms simulations compare to their actual performance post-occupancy? A follow-up question is: What are the parameters that impact differences between simulated and actual daylight performance in classrooms and whether these parameters can lead to the development

of a factor of reality (FR) metric to bridge gaps between design predictions and actual performance of buildings. To answer this question, this study compares the daylighting performance of four different classrooms with different daylighting systems, sky-view obstructions, and apertures types from both the teacher and the student's perspectives. The paper builds upon a previous framework of sustainable design as a place experience (Elzeyadi, 2015). This framework acknowledges the complex systems of interactions between people and their indoor environments on multiple layers relating to multi-comfort parameters and perceptions of visual comfort and daylighting quality.

Methods

Study Setting

Previous studies suggested that daylight simulations are most effective if started during the conceptual design phase of the project (Drosou, Brembilla, & Mardaljevic, 2016; Elzeyadi 2013). Following this recommendation, a fully integrated daylighting design process was adopted for a new K-5 Elementary school in Eugene, OR – ASHRAE climate zone 4C (Fig. 1). The design team engaged in the daylighting design process throughout the different phases of the project from conceptual massing, schematic design, design development, and construction documents studying 10 different design iterations for the major educational and common-use space types of the project.

Figure 1: An aerial view of the school (top, courtesy of Pivot Architecture), and model used for simulations in IES-VE (bottom).

Simulation process

The comprehensive simulation analysis evaluated daylighting distribution, glare, and annual dynamic daylighting metrics (IES-LM-83-12). The different design options were modeled in Autodesk Revit and

imported into Integrated Environmental Solutions – Virtual Environment (IES-VE) for daylighting simulations using both the FlucsDL module and Radiance Engine of the software.

The simulation parameters were controlled across all iterations using ASHRAE climate zone 4C TMY3 files for Eugene, OR. The space properties were simulated by adjusting the Light Reflectance Value (LRV) of the ceilings at 80%, the walls at 70% and floors at 20%, respectively. Internal and external light-shelves and skylight wells were modeled in a bright white paint of LRV at 92%. Clearstory, transom windows, and skylights were simulated with a T_{vis} of 69%, with the exception of view windows, which were modeled with a blue tint and a T_{vis} of 41% to avoid excessive glare. A pin-up wall in the classroom was modeled in bright colors with an LRV of 40% to simulate the resultant LRV of a typical classroom wall after posters are pinned-up to it. This added visual interest in the classroom and ensured that the LRV of interior walls is not altered when posters and assignments are pinned-up based on observed teacher's classroom use and behavior (Fig. 2).

Figure 2: Interior view of a sample classroom on the second floor (courtesy of Pivot Architecture).

Physical measurements

To investigate the research question related to the comparative analysis between simulated and measured performance, a daylighting Post-Occupancy Evaluation protocol (POE) was employed (Elzeyadi 2015). In this protocol, visual daylighting parameters and metrics were assessed and measured one year following full-occupancy of the 411 students' school. The POE assessment was conducted on a typical overcast equinox day in the afternoon. The short-term measurements of spatial daylighting distribution were conducted over a 5'x5' (approx. 1.5x1.5 meters) grid using a calibrated LiCor-210R photometric sensor connected to a LiCor handheld multi-meter. An external Li-Cor data logger connected to LiCor-210R photometric sensor logged outdoor sky illuminance levels in K-lux at 1-minute intervals.

Different imaging techniques were employed to document glare indices for a typical equinox afternoon daylight conditions. Glare assessment and metrics were computed by employing high dynamic range images (HDRIs) that

were taken from the teacher's perspective view-shed and a student perspective view-shed. Additionally, another HDRIs were taken looking towards the perspective of the window wall from the classroom entry, which provided an overall view of the classroom that would be experienced by all users as they enter and adjust to the brightness thresholds of the room. Both the student's and teacher's HDRIs employed a wide-angle and fish-eye lens to simulate each perspective and field of vision. Both types of HDRIs were recorded using the following equipment:

- For the overview image, it was taken at 70" (1770mm) height using a mirrorless Fujifilm X-Pro2 camera with extra-wide-angle lens (Fujifilm XF 10-24mm f/4 R OIS Lens).
- For the Fish-eye detailed image, it was taken from a seated position of both the teacher and the student view-sheds using a Canon G15 with a fisheye lens (Opteka 52mm 0.2x HD Professional Super AF Fisheye) attached to a tripod located at 44" (approx. 1100mm) to match teacher seated eye-level position as well as 38" (9614mm) to match a seated student eye-level position.

All HDRIs comprised of 5-7 bracketed images that were combined using 'hdrgen' command-line (Anywhere Software) using a predetermined response function for each camera. Each HDRI was then cropped, resized to 800x800 pixels, masked, and calibrated for computing glare indices. Metrics were computed using the 'evalglare' command. This process was batch automated with these commands in order.

The on-site POE assessment focused on four critical classrooms of the school that exhibited variations in daylighting systems and sky-view angles. The four classrooms were south facing, two of which opened to a courtyard wing on the first floor (C1) and second floor (C2). The other two classrooms faced outwards to a view of nature without any building obstruction on the first floor (O1) and second floor (O2) (Fig. 3).

All classrooms had a combination of south-facing perimeter clear story windows with an exterior and interior daylight shelf, south facing shop-front view window with low T_{vis} (41%) on the corner of the room, and a transom interior window to harvest daylighting from the connected daylit corridors. The large view window had an integrated fixed exterior solar shades and internal micro-perforated gray roller blind shades with a T_{vis} (11%). The second-floor classrooms had a similar daylighting system in addition to three distributed skylights placed 18' from the perimeter window wall with a skylight to floor ratio (SFR) of 8% (Fig. 3 & 4).

Figure 3: The four-sampled south-facing classrooms investigated. The number after the letter refers to the floor.

Figure 4: 2nd-floor classrooms with side and top lighting (above); 1st-floor classrooms with side lighting only (below).

Results

Table 1 displays the results comparing both yearly and point-in-time simulation output with point-in-time actual measurements in the classroom. Due to limitations in the POE time frame and limitations in accessing the classrooms during a typical school year, the study could not replicate annual daylight metrics, hence the comparative analysis focused on point-in-time comparisons. In general, measured illumination levels were higher than simulated levels for most of the daylight metrics studied (e.g. Avg. Illuminance (E) and % Area above 300 lux). In contrast, daylight factor (DF%) was consistently lower in measured conditions over simulated ones for all four classrooms. Similarly, glare metrics, such as Daylight Glare Index (DGI) were consistently lower in measured conditions of the POE over simulated conditions in IES-VE Radiance.

For classrooms on the first floor, simulations consistently predicted higher average illuminance and DF for the exterior classroom compared to the one on the courtyard. Measurements found only slight differences in DF and average illuminance between these two classrooms. Figure 5 shows the percentage of area >300 lux as simulated and predicted. As can be seen from the graph, simulations underestimated the percentage but followed a similar trend to that of the measured. highest percentage of area meeting the 300 lux daylight level threshold was for classroom C2 at 60.8% and 100% whereas the lowest percentage was for C1 at 13.9% and 33% for simulated and measured, respectively (Fig. 5 & 6). Figure 7 shows a comparison of the teacher's view in classroom O1 showing a rendering and a false color image of the luminance distribution.

Table 1: daylight and glare metrics for the studied classrooms as simulated (Sim.) and measured (meas.). The variable 'E' refers to horizontal illuminance.

		Annual metrics				Point-in-time metrics				
		sDA 300 lux - 50%	DF (%)	Avg. E for overcast sky	Avg. E for sunny sky	Avg. E	Avg. DF (%)	Area > 300 lux (%)	Student's view DGI	Teacher's view DGI
C1	Sim.	80%	2.7%	231	733	192	1.5%	14%	22.5	22.7
	Meas.					368	0.4%	33%	9.3	14.1
C2	Sim.	100%	5.7%	479	1282	464	3.5%	61%	23.4	22.3
	Meas.					1033	2.6%	100%	10.0	10.0
O1	Sim.	80%	2.8%	241	1862	241	2.8%	19%	22.2	22.7
	Meas.					357	0.5%	42%	7.05	15.5
O2	Sim.	90%	4.5%	380	2330	380	4.5%	24%	10.7	23.0
	Meas.					742	1.8%	100%	4.9	13.8

Figure 5: Spatial daylighting distribution as simulated and actual performance of the 4 classrooms studied.

Figure 6: Average illuminance as simulated and measured for the 4 classrooms studied.

Findings & Discussion

Further comparative analysis of both glare metrics and daylight distribution inside the four classrooms revealed interesting patterns of corroboration between simulated and actual performance. The polar plot in Fig. 8, displays the same trends in DGI values for both student and teachers between simulated and actual performance. While simulated DGI were consistently higher than actual performance, both sets of data reveal that glare is in the tolerable to unnoticeable levels for students and teachers.

A decrease in the DGI of the actual daylight performance might be due to the addition of paintings and posters on the classroom walls that reduced walls LRV, as well as the addition of furniture and materials in the room of lower LRV values than assumed in the simulation. This points to the fact that specified material LRV might not match those finishes in the actual space. Furthermore, other variables like dust, wear and tear, and maintenance issues would alter the LRV of materials from those in the specifications and simulation assumptions (Figure 7 & 8).

In addition, these differences in DGI could be due to limitations in the range of brightness levels captured by the camera as compared to those captured in simulation (Suk & Schiler, 2013). Field assessments rely on camera and lens capabilities which are not accounted for in simulations. Another possible set of parameters for the discrepancies are errors in measurements due to limitations in equipment, calibration, position of measurement, and the impact of the researchers position in space on the light measurements and values. This highlights the need for studies to examine these factors further.

Anecdotal comments received by the occupants indicate the presence of glare when students used a tablet in the area near the window. This is a challenging situation to simulate because any small variation in screen angle could affect the level of glare and reflections experienced. One way to alleviate this is to create designed pools of light scenarios with multiple light zones within each classroom where students can engage in different learning modes and devices. Similarly, the presence of direct sunlight on the teaching board, which was caused by an unintentional gap between the light shelf and window mullions. This was a result of a construction oversight related to a structural bracing system. This highlights the need for

daylight system commissioning to ensure that these systems are built as designed.

Figure 7: Comparative visualizations of glare and luminance distributions for both simulated (bottom) and actual classroom (top).

Figure 8: A polar plot comparison of DGI values for all classrooms for teacher and student views.

Another explanation for the discrepancies in performance might be attributed to the classroom furniture layouts. In the four classrooms studied, there were three different furniture layouts: rows, circular tables, and clusters as can be seen in Figure 9. During design, it is practically difficult to account for all possible furniture configurations and corresponding view directions. One suggestion is to employ the adaptive zone concept (Jakubiec & Reinhart, 2012) where students can adjust their seating arrangement to reduce perceived glare. This will require the specified areas of the classroom to be much larger to allow students a certain degree of freedom in changing their seating positions. Currently, school design guidelines do not allow for this excess in space and added construction budgets.

Like observations from previous studies (Drosou, Brembilla & Mardaljevic, 2016), the use of excessive electric lighting by the occupants in a successful daylit classroom persists. In interviews with some of the teachers, there were complaints related to excessive light levels in the classroom. Upon inspection, the teachers were used to fully turning on electric lighting regardless of the amount of daylight available in space. This might have led to overly bright spaces that exacerbated perceptions of glare level beyond the computed DGI & DGP levels. These issues are discussed in a forthcoming paper by the authors with further yearly comparisons of eight classrooms and common spaces in the school.

Figure 9: Plans of the furniture layouts as adjusted by occupants in the examined classrooms.

Further comparisons were performed between the two daylighting strategies employed in the studied classrooms; clerestory windows with light shelves (classrooms on the first floor: O1 & C1), and clear story windows with modular skylights (classrooms on the second floor: O2 & C2). Overall, the simulated DF values were much higher than actual performance, which might indicate a discrepancy in estimating the direct component (sky-view) and internal reflectance component and their contributions to light levels inside the classrooms (Fig.10 and Fig.11). This could be due to differences between simulation assumptions and actual conditions where the measurements were made.

For example, the impact of changes in LRV on daylight performance was shown to be highest for changes in LRV values for ceiling and walls followed by ground and floor (Brembilla, Mardaljevic, & Hopfe, 2015). This impact also varied by calculation method.

Based on the above, it is likely that differences would arise between simulated and actual performance of daylighting systems. These differences can be addressed and accounted for by incorporating a Factor of Reality (FR) similar in concept to correction factors utilized in the structural design, for example. The FR for daylight performance should account for the different sources that can cause discrepancies between physical measurements and simulation results, including:

1. Deviations between actual and simulated sky conditions in terms of direct and diffuse irradiance, sky cover, and horizontal illuminance. In IES VE, horizontal illuminance under an overcast sky is estimated to be about 12,000 lux. In this Study, although under overcast sky conditions, mean

horizontal illuminance was 46,797 lux. To address this limitation, DF was the primary metric used. When the use of dynamic daylighting metrics is desired, another set of simulations should be generated after measurements have been collected in the field to attribute for outdoor horizontal illuminance levels on the site.

2. Differences in simulated versus measured environments. These differences may result from slight changes to space design and/or occupant's behavior such as changes to LRV of interior finishes (e.g. location of posters on the walls), shade position, the location of furniture, cleanliness, external obstructions, etc.
3. Measurement-related deviations such as that caused by time of measurement, space location, and equipment-related errors as well as limitations.

Figure 10: A perspective showing the location of points used for comparison between simulations and field measurements. One set of points is in front of the view window while the other is in front of the clerestory window.

Future studies

The aforementioned deviations between simulations and actual performance warrant further studies to determine the extent to which different variables and categories influence physical lighting and glare measurements. Once determined, these different factors can be combined into a Factor of Reality (FR) correction index that architects and engineers can utilize at early simulations to reduce differences that are due to variability in external lighting conditions, field measurements, and occupant's response to better predict actual daylighting performance. Isolating these effects would help to more accurately assess the effects of building design on daylight performance.

While this paper did not investigate the relative importance of the three categories mentioned, Table 2 shows a conceptual summary of the variables within each category. It is expected that the impact of these variables depends on space type, coordination between design and construction teams, as well as the operation and occupancy of such spaces. To develop the proposed Factor of Reality, more studies are needed to determine

the impact of each variable in both direction and magnitude. Lastly, because the ultimate goal of daylighting design is to increase the comfort and satisfaction of occupants, future studies should examine developing a factor of reality for subjective assessments based on simulated or measured data. Another set of variables such as age, tasks, etc. are expected to shape this factor.

Figure 11: Daylight factor for classrooms O1 and O2 through the clerestory window (top), and through the view window (bottom).

Table 2: The variables that can impact daylight performance in schools.

Sky Condition	Physical Environment	Measurement limitations
<ul style="list-style-type: none"> -Solar irradiance. -Sky luminance map. -Horizontal illuminance. 	<p>Space Design:</p> <ul style="list-style-type: none"> -Space and aperture properties. -Obstructions. <p>Operational:</p> <ul style="list-style-type: none"> -LRV (e.g. posters and handouts). -Shade control. -Furniture layout. -Cleanliness and maintenance. 	<ul style="list-style-type: none"> -Equipment-related errors. -Researcher error and position in space. -seasonal sky conditions discrepancies during measurements

Conclusion

Current daylighting design practice for K-12 school design face several challenges between achieving dynamic daylighting metrics and the management of glare for both the teachers and the students. Simulation tools and programs offer promise in eliminating guess-work and provide evidence-based design decisions to predict daylighting performance. As this paper presents, gaps between simulated and actual performance persist even with detailed simulation models and inputs. It suggests that the concept of a Factor of Reality (FR) needs to be carefully calculated for various climate zones and sky conditions to bridge the gap in the predictive power of simulation models in meeting actual performance. The suggested FR would take into considerations various inconsistencies of LRV of materials, human behavior, maintenance, dynamic sky conditions, and modeling limitations. This paper is aimed at starting this discussion.

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Nomenclature

ASE:	Annual Sunlight Exposure
DF:	Daylight Factor
DGI:	Daylight Glare Index
DGP:	Daylight Glare Probability
FR:	Factor of Reality
LRV:	Light Reflectance Value
sDA:	Spatial Daylight Autonomy

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