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Application of Simulation-Based Metrics to Improve the Daylight Performance of a Secondary School, An Approach for Green Building Designers and Architects

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Abstract

Visual comfort affects the quality of classrooms as well as student learning. A practice-oriented approach discovers how the gap between academic research and its application in building design can be addressed. Nevertheless, the physical characteristics design of daylighting systems, including window sizes, shapes, dimensions, and materials, are considered fundamental challenges for their practicability. In this study, the physical characteristics design of daylighting systems, including window sizes, shapes, dimensions, and materials, are considered in a designed sample school, and the daylight metrics were analyzed to achieve more trustworthy and applicable daylighting systems. Grasshopper (Honeybee-Ladybug), as a parametric control method, was applied to simulate the daylighting quality for various educational spaces in a secondary school in Sanandaj City, based on average 'Daylight Factor', 'Daylight Autonomy', 'Useful Daylight Illuminance', and 'Annual Sunlight Exposure'. These metrics were examined to discover the relationship between window size and positions on visual comfort. The results indicate daylighting assessments are a solid approach to revising the architectural design mistakes at the primary designing phase. Architects and other building designers or energy consumption assessors can apply the design improvement process to present more sufficient and successful architectural details. This is a fundamental step toward the implementation of green buildings.

Keywords
Daylighting; green school design; climate-based daylight modeling; illuminance; spatial daylight autonomy; annual sunlight exposure

1. Introduction

In architectural and building design, the adjustment of daylighting is an essential step to control indoor comfort in terms of visual quality. This multi-dimensional task affects other aspects of the indoor environment, such as thermal comfort and occupants' mental state. Daylight has both physical and psychological impacts. Different factors affect visual comfort, such as sufficient daylight and uniform distribution of illuminance level, lack of glare or contrast in the working plane, characteristics of the shape, window-to-surface ratio, and glazing properties [1, 2]. Simulation software programs, which are powerful tools for studying the environmental performance of buildings, have become widely available. Using simulation tools at the early design stage of architecture, it will be possible to predict the environmental performance of buildings and user comfort.

The daylight calculation method can be categorized into static and dynamic or climate-based daylighting modeling (CBDM). DF as a static method can be introduced as the advanced attempt to measure daylighting [3]. In architectural design, a daylight factor (DF) is the ratio of the light level inside a structure divided by the light level outside the structure in an overcast sky situation [4]. It is independent of window orientation and time. In some cases, the difference between indoor and outdoor light levels is the cause of contrast glare. DF inherently takes into account this type of glare [5]. One of the advantages of DF is considering the room characteristics such as the window area, glazing transmittance, the ratio of window surface to room surface area, and the fraction of visible sky [6]. Moreover, DF may not be as precise as CBDM metrics, but it is more generalizable [7].

Dynamic metrics, including DA, cDA, mDA, sDA, and UDI, are proper for evaluating visual performance, indoor daylight distribution, glare, and daylight-linked lighting controls [6]. They announce long-term performance against the definition of comfort limits, considering time series of sky luminance derived from representative weather datasets. Among daylight metrics, sDA, and ASE can obtain spatial and temporal daylight conditions in single metrics [3]. Climate-based design is vital in increasing the resilience of buildings affected by interactive, complex, and changing characteristics depending on various factors. Bydogan and Ozkantar [2] have reviewed the energy and daylighting guidelines related to the schools. In Table 1 some of them with their metric criteria were presented.

Table 1 Standard for daylighting design of school buildings.

COUNTRY/PUBLISHING ORGANIZATION	YEAR	NAME	METRIC
SCOTLAND/Smarter Scotland Scottish Executive	2020	Building Standards Technical Handbook 2020: Nondomestic	DF
Ireland/Planning & Building Unit Department of Education and Skills	2013	TGD-022 Primary Schools Design Guidelines (for Classrooms)	DF
China	2013	GB 50033-2013 Standard for Daylighting Design of Buildings	DF
USA/ASHRAE	2018	Advanced Energy Design Guide for K-12 School Buildings	sDA
U.S./Washington Sustainable Schools Protocol	2018	Criteria for High-Performance School (K12)	sDA
ENGLAND	2014	(U.K. Education Funding Service	sDA-UDI

Certifications like BREEAM [8], LEED [9], and WELL [10] use performance evaluation criteria for sustainable design. Daylight optimization is one of the principal points of these certifications. As a sustainable building rating system, LEED (Leadership in Energy and Environmental Design) v4.1 emphasizes passive design and daylighting approaches and has a scoring system for daylighting in educational buildings [2]. For example, ASE and sDA are two LEED's daylighting criteria. LEED awards Credit Points 1, 2, and 3 to the sDA300/50% for the regularly occupied floor area at least 40%, 55%, and 75%, respectively.

The daylighting metrics, quality, and methods were analyzed in several studies. Multiple criteria related to building façades, internal dimensions (area and space depth), and window sizes contribute to the indoor brightness quality. Bakmohammdai et al. [11], for enhancing daylight and energy efficiency, used a two-phase optimization approach to optimize the geometry of a classroom in Tehran. Building orientation, wall inclination angle, number of windows, WWR, and glazing material were considered as the design parameters in the optimization process. They calculated TEUI, LEUI, CRT, Da, and UDI in the first phase. After selecting the optimum design solutions in the first stage, values of ASE and DGP were implemented to assess visual comfort. Their observations show WWR notably impacts the cooling, heating energy, daylight metrics (UDI and DA), and electric lighting energy while building orientation highly influences ASE and occupant thermal comfort. In another study [12], WWR, glass material, wall construction, and shading device configuration were adjusted for optimum performance in daylighting and energy consumption. Atthaillah et al. [13] considered horizontal shading depth, height, and window-to-wall ratio for climate-based daylighting optimal design model in Indonesian school classrooms with symmetrical or asymmetrical openings on the opposing façades. $UDI_{250\text{-}750lx}$ was proposed as the reference metric; aUDI100-3000lx and ASE1000,250 were also calculated. For the symmetrical case, the result showed that WWR between 13%-19% is the most efficient.

Yu et al. [14] reviewed the thermal-daylighting balance in which the balance between the heat from the infrared solar spectrum and sufficient illuminance for comfortable vision was analyzed. In a study [15], the authors recommended the concept of Minimum Daylight Autonomy to link it with the Daylight Factor. The study advised a method for the calculation of minimum daylight autonomy.

Baloch et al. [16] have assessed the correlation between test scores of 2670 elementary students in logical and mathematical exams and classroom daylighting conditions. They found a clear relationship between the scores and type of window shading, percentage of windows facing south, latitude, and window glazing type. The highest impact relates to the window-to-floor area ratio (WFR). In other words, the results showed daylighting has a direct influence on students learning.

Several studies used daylight metrics and field surveys (questionnaires) to evaluate visual comfort and find the correlation between various metrics. Liu et al. [17] conducted field surveys (18 classes in Chinese schools) and illuminance measurements to discover the correlation between daylighting metrics and students' subjective evaluations (daylighting adequacy, satisfaction, and glare). Additionally, they attempt to find the appropriate thresholds of metrics. The considered metrics involve static (DF) and dynamic metrics (sDA, UDI, ASE, DGP). Their study indicates sDA450/50% ≥50% was preferred by student assessment, but ASE was not correlated with student evaluations in north-facing classrooms. Zomorodian et al. [18] were investigating the ability of dynamic metrics (SDA300/50%, UDI300-3000/50%, DA 300 Average) and static metric (DF) of daylight and glare (ASE, sDGP) to explain the perception of human subjective responses in classrooms. According to the simulation and questionnaire, a high correlation was observed between students' perceptions and dynamic daylight metrics, sDA300/50% and UDI300-3000/50%, and in defining the daylight area, sDGPexceed is more compatible than ASE to perceived discomfort glare.

Vaisi and Kharvari [19] evaluated the daylight regulation in Iranian buildings using the Daylight Factor (DF). Based on internationally validated standards such as BREEAM, LEED, and Green Star, they proposed an optimal range of WFR (window-to-floor ratio), 15-24%, which also regulates overheat and glare.

In a recent study [6], optimizing solar daylighting reduced artificial lighting energy while the cooling load was fixed. The results approved the positive role of light shelves in increasing lighting uniformity. In another study [20], several criteria forced in Sweden, i.e., 2 performance criteria announced by the EU Standard EN17037, Daylight Factor suggested by BREEAM, and a climatical-related criterion known as a UDI metric, have been analyzed. The results showed that the Vertical Sky Component and WFR, compared to other geometric measures, affected daylighting significantly.

The role of latitude and building orientation (hypothetical northwest/southeast-oriented) on the solar lighting illuminance level was assessed [21] using Daylight Factor, Daylight Illuminance (DI), and Daylight Autonomy (DA). The results indicated that a high level of daylight in the afternoon hours (predominantly in the summer season) passed into the residential buildings on the rear side; nevertheless, 67% of the total houses were below the 2% DF threshold. In this regard, most of the time, the occupants in rear-side rooms are satisfied with illumination levels above 300 lux.

Applying parametrically-angled reflective slats that can react to the sun's position to gain maximum daylighting inside a deep space, the authors [22] have developed a daylighting supply system by changing the slats' shape and size to realize the optimum balance between practicality and performance. This research indicated that decreasing the louver size and altering the slat's curvature can considerably grow the daylight coverage percentage inside the deep room from 93% to 98%. At the same time, the standard illuminance of 300-500 lux was provided. Accordingly, several researchers [23-26] investigated improving daylighting to decrease artificial lighting energy.

In other studies, Vaisi et al. [27-30] have investigated the energy benchmarks for various types of buildings, such as university buildings, offices, and school buildings. The daylighting analysis is connected with energy consumption. Therefore, if the quality and quantity of solar lighting are improved, it can be said that this strategy will indirectly affect energy saving. Both daylighting methods (static and dynamic) have advantages and disadvantages. Daylighting metrics of this study have been selected by reviewing various guidelines published by different institutions and organizations. Furthermore, sDA and ASE were chosen as they align with LEED v.4.1.

The metrics measured by Honeybee are DA, ASE, UDI, DF, and Daylight Autonomy (DA), which measures whether a given space, such as a classroom, gets sufficient daylight on a work plane during standard operating hours on an annual basis. The Illuminating Engineers Society of America (IESNA) [31] considers a space adequately daylight when it is above 300 Lux for 50% of the year. The sDA can predict indoor daylight uniformity but cannot evaluate the visual glare [6].

The other indicator, i.e., Annual Sunlight Exposure (ASE) identifies surfaces receiving too much sunlight that may cause visual discomfort (glare) or additional cooling loads (overheating). ASE measures the percentage of the work plane exceeding the threshold of 1000 lux more than 250 occupied hours per year. The LEED standard system defines sDA and ASE metrics [32, 33].

Useful Daylight Illuminance (UDI) is a parameter of daylighting presented by Mardaljevic and Nabil in 2005 [34]. This metric relies on an hourly scale categorized into 3 illumination ranges i.e., 0-100 lux, 100-2000 lux, and over 2000 lux. UDI considers full credit only for the range of 100-2000 lux, advising that horizontal illumination thresholds outside this range are not helpful (dark or glare). There is a challenging argument about 2000 lux as an 'upper threshold' that, more than that, daylight is not favorable due to the potential for glare or overheating. The graphical values indicate the percentage of the floor area that meets the UDI criteria should be more than 50% of the time.

1.1 Objectives

The current study calculated and discovered a better fenestration dimension to naturally light the educational spaces designed for a secondary school. In the project, the authors have examined the effect of the position of windows to gain sufficient solar spectrum. Finally, it provides a guideline for building engineers and architects to be used in the architectural design process.

1.2 Contribution to the Knowledge

According to the reviewed literature, most studies focused on the daylighting analysis and its relationship with energy consumption. It was found that there is a link between window sizes, position, and solar gain. However, the research gap is the best dimension for a window installed on the south or north elevation. These criteria are different in various climatical zones. This study developed a practice-oriented method to calculate the correct size and position of windows for the 35° northern hemisphere latitude. The technique fills the gap in practice when standards and building design guidelines need to deliver more accurate policies.

2. Materials and Methods

For the assessment of daylighting, in this research, several basic metrics of daylighting calculation, including Daylight Factor (DF), Daylight Autonomy (DA), Spatial Daylight Autonomy (SDA), 'Useful

Daylight Illuminance' (UDI), and 'Annual Sunlight Exposure' (ASE) were applied. To do so, as a visual programming interface, Grasshopper provides the stage for visualization and control of the geometric parameters. Consecutively, the environmental plugins of Ladybug and Honeybee were applied to calculate the amount of daylight received. For simulation, Honeybees are connected to Radiance as the validated simulation engine. Honeybee tool based on Radiance offers detailed daylighting modeling that is more applicable in the primary phases of the building's design [35, 36].

An annual daylight simulation was conducted for an Iranian school. Based on the National Building Regulations of Iran, the educational centers are open weekdays (from Saturday to Wednesday) from 8 am to 2 pm. The EnergyPlus Weather (EPW) data format for Sanandaj was extracted and imported into the Ladybug plugin to develop the climate-based daylighting model. Since the designed school is located in the center of an occupied site and due to the low height of the surrounding buildings and the long distance between the target building and adjacent buildings, the main spaces of the school obtain adequate daylight from the north and south sides. Therefore, the neighborhood wasn't taken into account in the simulation.

Regarding the occupation time and period, secondary schools in Kurdistan are mostly open 5 days a week from 7:30 to 14:30. The holidays started annually from the 20th of June to the 22nd of August. In addition, there are about 13-15 days of the new year holidays. The actual local weather data of 20 recent years were applied as an EPW file in Grasshopper.

2.1 Site Plan

A new green school, i.e., 'Green Millennium Girls School', was designed in the conventional neighborhood (Faizabbad) in Sanandaj City, Iran. Sanandaj is the center of Kurdistan province, located at latitude 35.326306° and longitude 47.003539°. The Kurdistan government has a plan to build a nearly zero-energy building. The area of the existing site is 4,558 m^2, as illustrated in Figure 1. The new school (in the design phase) is located on the north side of Takhti Street and is surrounded by other educational facilities, sports centers, and retailers.

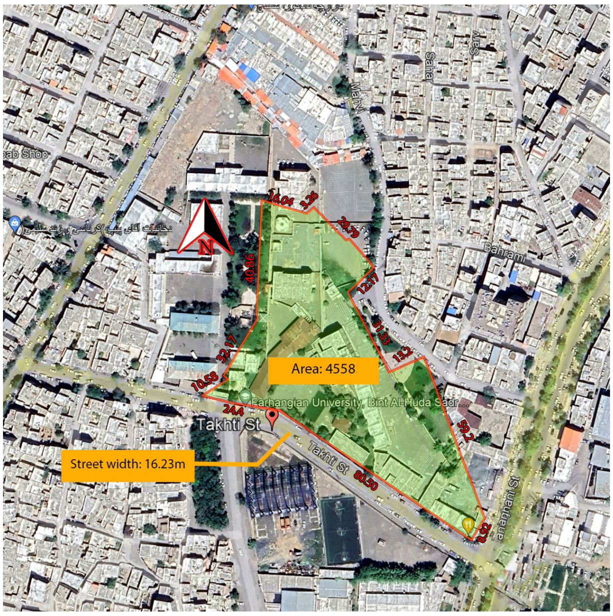

Figure 1 Site plan of Green Millennium Girls School.

The ground floor plan of the sample-designed school (Green Millennium) is presented in Figure 2. To assess the daylighting, 3 classes (Classes A, B, and C) were selected; two are theoretical, and the others are workshops. In addition, an office room and the lobby were also assessed in terms of sufficient daylighting.

Figure 2 Ground Floor plan and perspective of the selected spaces for daylighting analysis.

3. Results and Discussions

Table 2 shows the classes, office room, and Lobby's dimensions, area, and other necessary information. For example, the area of Class A is 37 m^2, with 2 windows, while the WFR percentage is approximately 27%.

Table 2 Sample spaces and metrics in detail.

Name	Floor area (m^2)	Window area (m^2)	Numbers of windows	WFR (%)	DA (%)	UDI (%)	DF (%)	ASE (%)
Class A	37	10	2	27.02	90	68.78	4.36	52.60
Class B	38	9.90	2	26.05	53	83.63	2.90	7.90
Class C	47.40	8	2	16.87	52	68.30	2.33	31.60
Office	23.27	4.50	1	19.40	48	76.48	2.65	27
Lobby	140.88	22.7	3	16.10	38	74.25	2	16

In addition, the other necessary data applied in the analysis is presented in Table 3.

Table 3 Simulation characters.

Parameters	
Work plane height (m)	0.75
Grid size	0.50
Transmittance of window	0.50
Ambient bounce	6
Ambient divisions	4096
Ambient accuracy	0.1

3.1 Results of DA and sDA Assessments

The results of analyzing the DA of Classes A, B, and C, as well as the Lobby and the sample office, are presented in Figure 3 and Figure 4. The percentages of sDA (300/50%) of Classes A, B, C, Office, and Lobby are 90%, 53%,52%, 48%, and 38% respectively. Based on LEED standard (LEED BD + C: New Constructionv4.1 - LEED v4.1), all the spaces except the lobby passed this metric. The deepness of the Lobby affected lower daylighting; however, it is not dark.

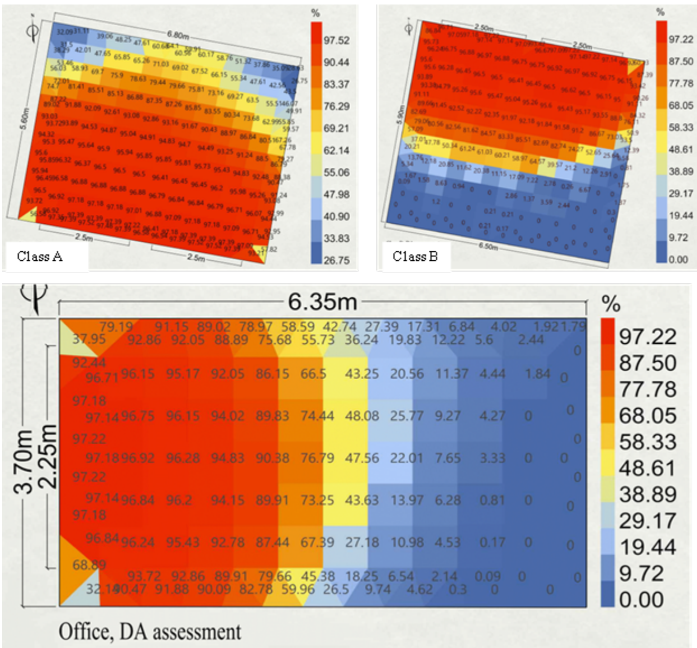

Figure 3 Daylight Autonomy assessment.

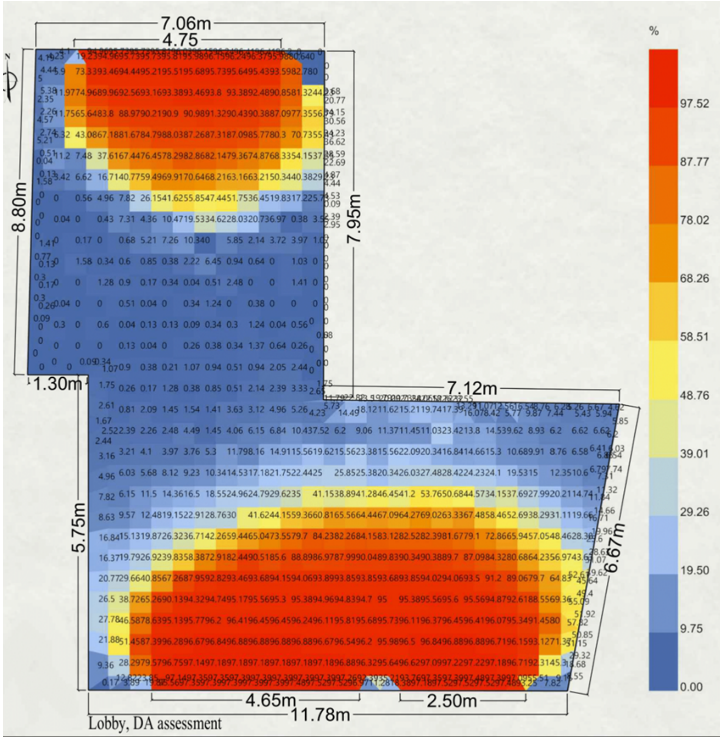

Figure 4 Daylight Autonomy assessment.

3.2 Results of ASE Assessment

The analysis for ASE (1000/250 h) was conducted, and the results are presented in Figure 5. The ASE of Classes A, B, C, Lobby, and the sample office are 52.60, 7.90, 31.60, 27, and 16. This means spaces such as Class A, Class C, and Lobby need to address glare.

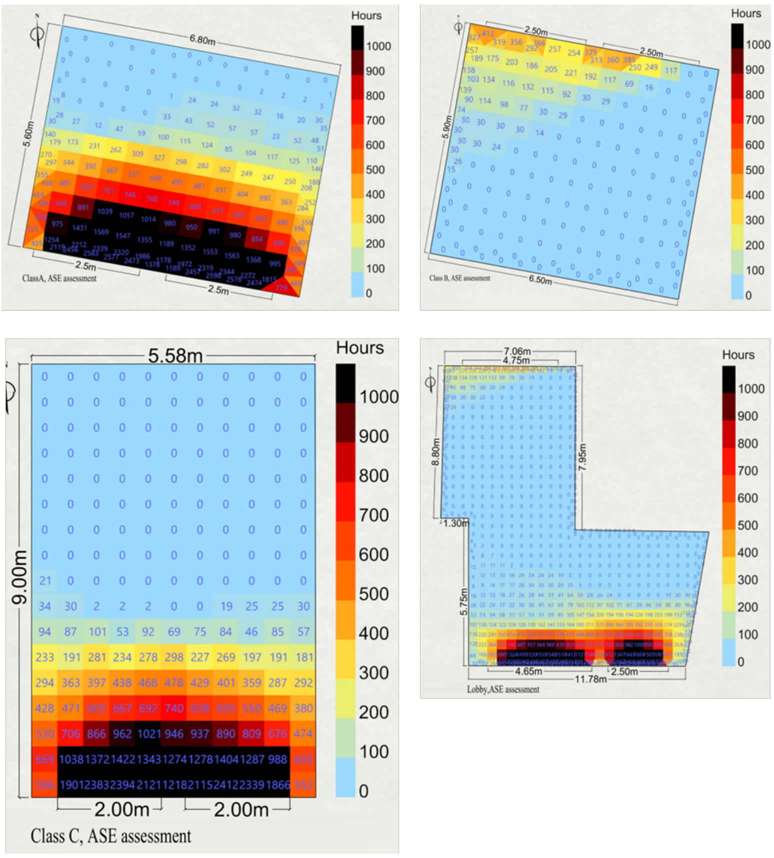

Figure 5 ASE assessment.

3.3 Results of UDI

The Useful Daylight Illuminance (UDI) was assessed, and a sample result for Class C is presented in Figure 6. According to the analysis, the UDI of Classes A, B, C, office, and Lobby are 68.78, 83.63, 68.30, 76.48, and 74.25, respectively. All these spaces passed the UDI metric.

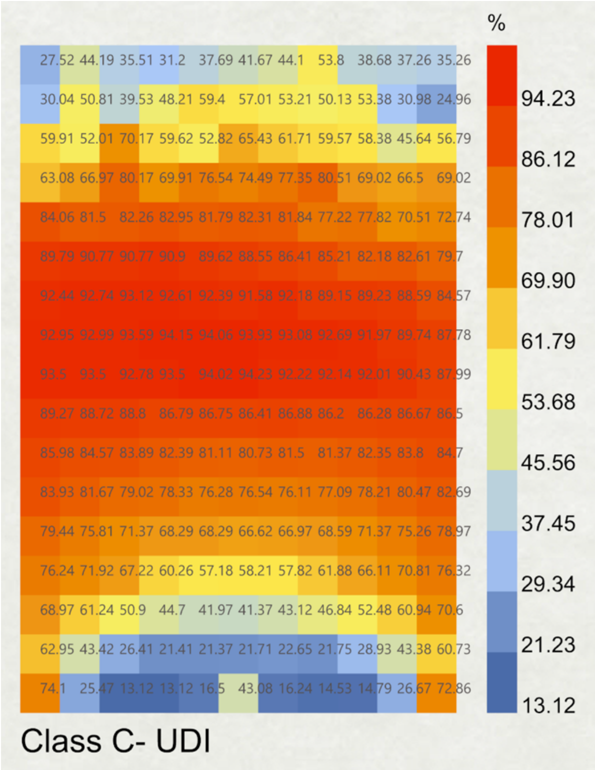

Figure 6 UDI of Class C.

3.4 Results of DF Assessment

The results of DF analysis for Class A, B, C, Office, and Lobby are 4.36%, 2.90%, 2.33%, 2.65%, and 2%, respectively (Figure 7). Based on the LEED standard, all the spaces passed this metric.

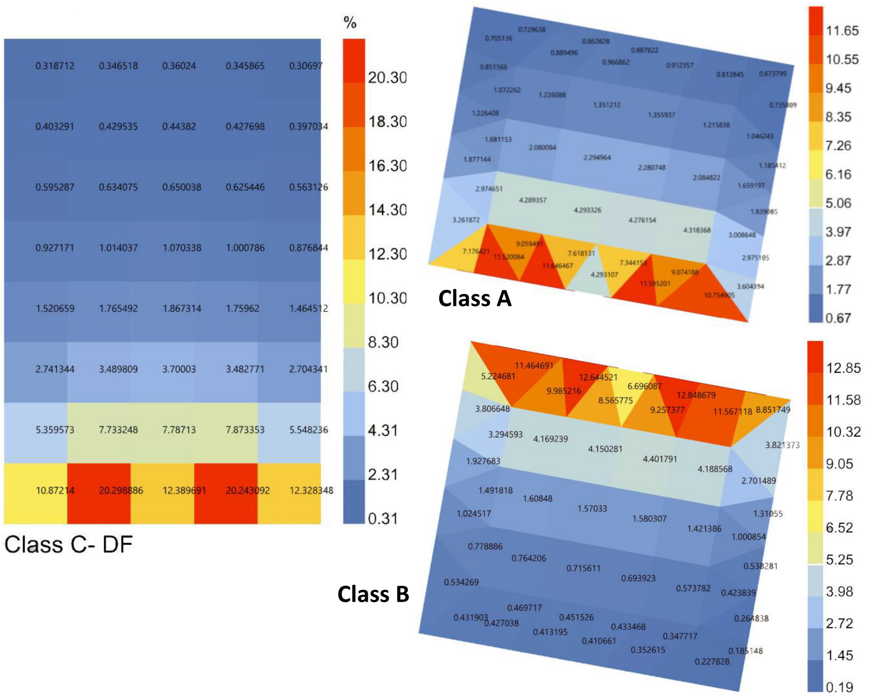

Figure 7 DF assessment.

4. Revising the Architectural School Design in Terms of the Best Daylighting

This section presents how the simulation results were translated into the architectural design alterations and how the maps were corrected based on daylighting benefits to pass the standards. Based on the analysis, it was discovered that Class C did not pass the ASE metric. Therefore, the architectural design was revised to cover this gap. The architects of Green Millennium Girls School changed the size and number of windows to prevent glare. Table 4 compares the primary parameters with the final architectural revised design. For example, the window area from 8 m^2 was reduced to 4.25 m^2. Accordingly, the WFR also was decreased from 16.87% to 8.96%. The revision has affected the ASE significantly, so the results show that the glaring risk was reduced from 31.60% to 10%. All the new metrics are acceptable now without any glare risk. Through this example, the author shows how building designers can control daylighting in the primary phases of architectural design. This methodology can be applied in all building design processes.

Table 4 Comparison between primary and the revised parameters.

Class C								
Parameters	Floor area (m^2)	Window area (m^2)	Number of windows	WFR (%)	sDA (%)	UDI (%)	DF (%)	ASE (%)
Primary Design	47.40	8	2	16.87	52	68.30	2.33	31.60
Revised Design	**47.40**	**4.25**	**2**	**8.96**	**52.86**	**73.12**	**2.08**	**10.00**

5. Conclusion

In this research based on fundamental daylighting metrics such as DF, sDA, and ASE, the authors developed a practice-oriented analysis to discover daylight quality and quantity in various educational spaces in a sample green school building. The project site is located in Sanandaj, which has a cold climate. Using the actual climate data (EPW file), the architectural design of a secondary school was revised at the primary design phase to obtain proper daylighting to pass BREEAM and LEED standards. The results indicated that Class C had a problem and gained extra daylight, which caused glare and overheating. Glare can also affect students' visual comfort and may reduce their attention and learning ability. Therefore, the primary architectural design was revised by adjusting the size of the window and designing a 0.60 m horizontal canopy, which addressed this gap. The method also presents an applicable guideline for building designers and architects.

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Author Contributions

Salah Vaisi presented the idea and research its structure. He provided the first draft and managed the work. Honia Modares Gorji was responsible for analysis such as daylighting and energy. She also worked on the draft. Narmin Shafei shared the architectural design, architectural details, and site analysis. Narmin also was responsible for proofreading.

Competing Interests

The authors declare that they have no known competing interests.

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