



Facade and Opening Design Strategies for Enhancing Natural Lighting Efficiency in Classrooms at SD Labschool UPI

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Abstract

Natural lighting is an essential aspect of elementary school building design, as it significantly influences visual comfort and learning effectiveness. However, many classrooms in Indonesia do not meet the minimum illuminance standard of 350 lux specified in SNI 03-6197-2020. This study aims to evaluate and optimize facade and opening design strategies to improve the performance of natural lighting at SD Labschool UPI. The research employed daylight simulations using VELUX Daylight Visualizer on two building floors without the assistance of artificial lighting to analyze light intensity and distribution. The results indicate that the first floor met the required standard, achieving average illuminance levels of 358.6 lux (March 21) and 350.3 lux (December 21). In contrast, the initial design of the second floor remained below the standard, with average illuminance values of 299.4 lux and 256.5 lux, respectively. Through the addition of corridor skylights, the optimization of building openings, and the implementation of a secondary skin as a shading device, the average illuminance on the second floor increased to 362.5 lux and 352 lux, with a more uniform light distribution and better control of glare potential. This study confirms that passive facade design strategies can effectively achieve the latest illuminance standards without relying on artificial lighting.

Keywords : Natural Lighting, Opening Design, Classroom, SD Labschool UPI, VELUX Daylight Visualizer

Strategi Desain Fasad dan Bukaan untuk Efisiensi Pencahayaan Alami pada Ruang Kelas, SD Labschool UPI

Abstrak

Pencahayaan alami merupakan aspek penting dalam perancangan bangunan pendidikan dasar karena berpengaruh terhadap kenyamanan visual dan efektivitas belajar. Namun, banyak ruang kelas di Indonesia belum memenuhi standar iluminansi minimum sesuai SNI 03-6197-2020, sebesar 350 lux. Penelitian ini bertujuan mengevaluasi dan mengoptimalkan strategi desain fasad dan bukaan untuk meningkatkan kinerja pencahayaan alami pada SD Labschool UPI. Metode yang digunakan berupa simulasi daylight menggunakan Velux Daylight Visualizer pada dua lantai bangunan tanpa bantuan pencahayaan buatan untuk menganalisis intensitas dan distribusi cahaya. Hasil menunjukkan bahwa lantai satu telah memenuhi standar dengan rata-rata 358,6 lux (21 Maret) dan 350,3 lux (21 Desember), sedangkan desain awal lantai dua masih di bawah standar, yaitu 299,4 lux dan 256,5 lux. Melalui penambahan skylight koridor, optimalisasi bukaan, dan secondary skin sebagai shading, iluminansi lantai dua meningkat menjadi 362,5 lux dan 352 lux dengan distribusi cahaya lebih merata serta potensi silau yang lebih terkendali. Penelitian ini menegaskan bahwa strategi fasad pasif mampu memenuhi standar terbaru secara efektif tanpa ketergantungan energi buatan.

Kata-kunci : Cahaya Alami, Desain Bukaan, Ruang Kelas, SD Labschool, VELUX Daylight Visualizer.

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Introduction

Background

The global energy crisis and the increasing carbon emissions generated by the building sector have elevated the role of natural lighting beyond merely supporting visual comfort. Today, natural lighting is recognized as one of the key elements of sustainable building design. The Government of Indonesia established Presidential Regulation (Perpres) No. 61 of 2011 concerning the National Action Plan for Greenhouse Gas Emission Reduction (RAN-GRK) [1]. This regulation represents the nation's commitment to mitigating climate change through various measures, including energy efficiency in buildings. Therefore, opening design strategies for efficient natural lighting not only affect building occupants but also contribute to energy conservation and sustainable development.

Natural lighting also plays a crucial role in creating a healthy and productive learning environment, particularly in classrooms within educational buildings such as elementary schools [2]. Appropriate facade and opening design strategies can achieve efficient natural lighting while minimizing dependence on artificial lighting [3]. Therefore, careful consideration of the architectural design aspects that influence the admission of natural light into classrooms is essential.

Several previous studies have evaluated natural lighting performance in educational buildings in Indonesia. An analysis of coastal schools in South Sulawesi revealed that the majority of classrooms still exhibited natural lighting levels below the Indonesian National Standard (SNI), with approximately 83.2% of classrooms failing to achieve the minimum illuminance requirement [4]. Furthermore, the study entitled "Daylight Comfort for Sustainable Educational Buildings" found that only 32% of elementary and secondary school classrooms in Makassar satisfied the required standards for natural lighting intensity and distribution [5].

Other studies have highlighted the influence of architectural elements on natural lighting performance. For example, research investigating the effects of opening design at SMA Negeri 1 Dolok Batu Nanggar found that the size, shape, position, and orientation of openings significantly affected natural lighting intensity within classrooms [6]. Previous studies have also emphasized that the reflectance of surrounding interior surfaces influences indoor natural lighting levels [7]. However, these studies generally focused on post-occupancy evaluations,

meaning that design improvements could only be implemented after the buildings had already been constructed.

Meanwhile, a study investigating the application of tropical natural design concepts in the classrooms of SMK Dewantara found that, despite optimizing the openings and building orientation, several classrooms still failed to satisfy the minimum natural lighting standard based on measurements of daylight intensity and opening dimensions [8]. These findings are consistent with an evaluation of natural lighting effectiveness in junior high school classrooms, which demonstrated that most measurement points remained below the required illuminance standard, indicating that the learning spaces had not achieved adequate lighting levels for visual activities [9]. Other studies have also emphasized that the previous Indonesian standard, SNI 03-6197-2000, which specified a minimum illuminance of 250 lux, is no longer sufficient to meet the visual comfort requirements of modern learning environments [9][10].

On the other hand, studies integrating natural lighting performance analysis during the early design stage through digital simulation, particularly those based on the latest SNI 03-6197-2020 standard, remain limited. Therefore, this study adopts SNI 03-6197-2020, which establishes a higher minimum illuminance requirement of 350 lux, ensuring that the lighting evaluation is conducted in accordance with the latest and more relevant standard [11].

This study seeks to address this research gap by evaluating and optimizing classroom opening designs using daylight simulation during the conceptual design stage. This approach enables the prediction of natural lighting performance early in the design process, allowing energy efficiency strategies and visual comfort considerations to be implemented proactively. Accordingly, this study adopts the latest standard by establishing a minimum illuminance target of 350 lux, thereby providing a more relevant assessment of lighting quality for contemporary learning environments than previous studies that relied on the former minimum standard of 250 lux.

The existing building of SD Labschool Universitas Pendidikan Indonesia (UPI), located on Jalan Raya Cibiru, Bandung City, is considered no longer adequate. The building is no longer capable of accommodating the increasing demand for educational spaces in terms of student capacity as well as supporting facilities. Therefore, this study

uses the Phase II redevelopment project of SD Labschool UPI, scheduled for reconstruction in 2026, as its case study. Daylight simulations were performed on the initial design using the VELUX Daylight Visualizer software.

The objective of this study is to evaluate the compliance of the opening design with natural lighting standards and to propose design recommendations that enhance both energy efficiency and visual comfort in a sustainable manner. This approach is expected to support decision-making during the architectural design process for classrooms and other elementary educational facilities.

Theoretical Review of Natural Lighting

The primary aspects of natural lighting design include illuminance, daylight factor (DF), and the uniformity of light distribution within interior spaces [12]. Illuminance measures the amount of light incident on a surface and is expressed in lux (lumens/m²) [13]. Appropriate illuminance levels are essential for preventing visual fatigue and enhancing the comfort of learning environments [14].

The daylight factor (DF) is defined as the ratio between the indoor illuminance measured on the working plane and the simultaneous outdoor horizontal illuminance under overcast sky conditions [15]. According to the international standard CIBSE (Chartered Institution of Building Services Engineers) Lighting Guide (LG) 10:1999, a DF value below 2% is considered insufficient and requires artificial lighting throughout the day, whereas a DF value above 5% indicates adequate natural lighting, with artificial lighting needed only during dawn or dusk [14]. This range is important for preventing both excessively dark areas and overly bright spots that may reduce visual comfort. Previous studies have demonstrated that even when a space satisfies the daylight factor standard, non-uniform light distribution may still reduce visual comfort and impair students' visibility [15].

According to SNI 03-6197-2020, the minimum required illuminance for classrooms is 350 lux (Table 1) to ensure visual comfort and support effective teaching and learning activities [11]. Designing openings for efficient natural lighting also requires consideration of the Window-to-Floor Ratio (WFR), which is the ratio of the total window area to the floor area. The recommended WFR ranges from 10% to 20% [16]. However, field studies and simulation analyses conducted on educational buildings in Thailand found that a WFR of 20% or greater

provides better natural lighting performance and more effective daylight distribution [17].

Table 1. Minimum Illuminance Requirements for Educational Spaces.

No	Educational Space	Minimum Average Illuminance (lux)	Minimum Color Rendering Index (CRI)
1	Classroom	350	80
2	Reading Room	350	80
3	Laboratory	500	90
4	Computer Laboratory	500	80
5	General Laboratory	300	80
6	Teachers' Room	300	80
7	Sports Room	300	80
8	Art Room	750	80
9	Auditorium	300	80
10	Lobby	100	80
11	Staircase	100	80
12	Cafeteria	200	80

Sourcer: SNI 03-6197-2020

In addition to natural lighting, Indoor Air Quality (IAQ) must also be considered. IAQ encompasses factors such as pollutant concentration, humidity, temperature, and air circulation [18]. Thermal comfort experienced by occupants also plays an important role. Thermal comfort is influenced by temperature, humidity, air velocity, and thermal radiation [19]. One of the factors affecting both IAQ and thermal comfort is ceiling height, which is generally designed to be at least 3 m, with an ideal height of approximately 3.3 m.

Methods

Identification of The Study Object Characteristic

The initial stage involved identifying the building characteristics and selecting classrooms as research samples using a purposive sampling approach to obtain spaces that were most representative of facade performance and natural lighting conditions. The Phase II Site Plan of SD Labschool UPI (Figure 1) illustrates three building masses connected by a basketball court serving as an open space between them. Building No. 1 represents the main elementary school building, while Building No. 2 represents the Phase II elementary school building, which serves as the case study in this research. The building is situated on a 22,182 m² site with a Building Coverage Ratio (BCR) of 60%, resulting in a maximum allowable building area of 13,309.2 m². The site is bordered by Jl. Pendidikan, Jl. Pandawangi, and Jl. Cibiru Indah I,

with the main entrance located on Jl. Pendidikan. The facade of the Phase II building is designed with an east-west orientation, which may result in non-uniform daylight distribution.

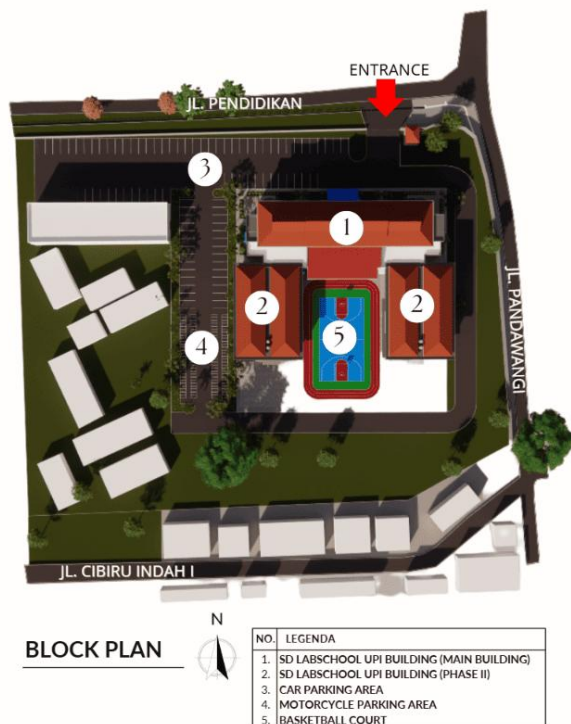


Figure 1. Block Plan of SD Labschool UPI, Cibiru, Bandung.

The building consists of two floors and serves primarily as a formal learning facility for elementary school students. Its primary users include students, teachers, and school administrators. This project was selected as the study object because it is currently being designed to meet educational standards that are user-friendly and environmentally responsive. The building elevations of the Phase II building (Figure 2) illustrate the classroom facades examined in this study, specifically those located on the second floor (indicated by the red dashed lines).



Figure 2. Elevations of the Phase II SD Labschool UPI Building, Cibiru, Bandung.

The classrooms on the first and second floors were selected using the typical classroom approach, which is commonly adopted in natural lighting performance

studies [19]. The floor plans of the first and second floors (Figure 3) show the spatial layout on each level. There are six classrooms, each measuring 8×7 m with a floor area of 56 m^2 . A corridor serves as the circulation space, while separate toilet facilities are provided for male and female users.

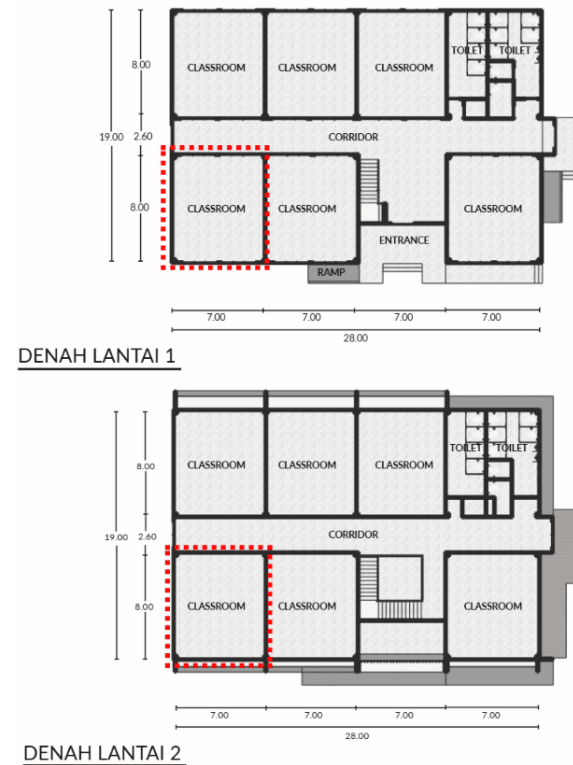


Figure 3. First and Second Floor Plans of the Phase II SD Labschool UPI Building, Cibiru, Bandung.

Determination of Natural Lighting Evaluation Parameters

The evaluation of natural lighting in the classrooms was conducted by considering several key parameters. These parameters include classroom dimensions, the size and position of the openings relative to the floor, and the building orientation, which faces east-west. According to SNI 03-2396-2001, indoor lighting conditions can be represented through designated measurement points. A horizontal working plane at a height of 0.75 m above the floor was established as the reference measurement plane. The Side Measurement Point (TUS) was positioned 0.50 m from the side wall and located at a distance equivalent to one-third of the room depth measured from the effective daylight opening. The room depth was measured from the effective daylight opening to the opposite interior boundary of the room [11].

Although SNI 03-2396-2001 specifies designated measurement points such as TUU and TUS, this study employed measurements across the entire working

plane using a simulation grid, with grid points located 0.50 m from the side walls (without openings). This approach was adopted to minimize excessive wall reflections that could reduce the accuracy of natural lighting measurements. The average illuminance value (lux) was calculated from all grid points, thereby providing a more representative assessment of the overall natural lighting conditions within the classroom.

VELUX Daylight Visualizer Modeling and Simulation

A three-dimensional model of the classroom was subsequently developed, and natural lighting simulations were performed using VELUX Daylight Visualizer to obtain illuminance distribution under various observation periods. VELUX Daylight Visualizer was selected because it provides a simple, accurate, and easily interpretable method for visualizing and calculating natural lighting performance. The simulation was conducted by importing the three-dimensional building model into the software, after which the building orientation and geographical location were configured according to the project data at a latitude of -6.9406736 and a longitude of 107.7252358 . By incorporating accurate location data, the simulation was able to represent realistic daylight conditions throughout the year.

Another factor influencing the effectiveness of indoor natural lighting is reflectance. Reflectance refers to the ability of materials (such as walls, floors, ceilings, furniture, and other surfaces) to reflect incident light. The higher the reflectance value, the greater the amount of light reflected into the interior. Conversely, lower reflectance values result in greater light absorption, causing the room to appear darker [17].

Based on data from VELUX, the reflectance values of materials surrounding the site and within the interior of the Phase II SD Labschool UPI building vary according to the material type (Table 2). Interior materials, including the white-painted ceiling (0.827) and the white-painted walls and columns (0.814), exhibit the highest reflectance values. The granite floor has the highest reflectance among the horizontal surfaces within the occupied space (0.851). Exterior materials, such as the surrounding concrete buildings (0.462) and clay roof tiles (0.321), have relatively low reflectance values. Wooden furniture surfaces, including doors (0.664), desks, and chairs (0.689), exhibit moderate reflectance values. Meanwhile, the painted basketball court surface has the lowest reflectance, ranging from 0.148 to 0.176.

Table 2. Reflectance Values of Site Surface and Classroom Interior Materials at SD Labschool UPI.

No.	Material	Material Type	Reflectance
1	Surrounding Buildings	Concrete	0,462
2	Basketball Court	Green Paint	0,176
		Blue Paint	0,148
		Red Paint	0,162
3	Floor	Granite	0,851
4	Walls	White Paint	0,814
		Blue Paint	0,162
5	Ceiling	Gypsum wth White Paint	0,827
6	Window and Door Frames	Aluminum	0,520
7	Concrete Columns	Blue Paint	0,814
8	Chairs and Desks	Wood	0,689
9	Doors	Wood	0,664
10	Roof	Clay Tile	0,321

The glazing material used in the initial design was Clear SNFL (Super Neutral Filter Low-E) glass, which has a visible light transmittance (VLT) of 50%. Transmittance is defined as the ratio of the amount of light transmitted through a material to the amount of incident light falling upon it [16]. This value represents the material's ability to transmit visible light, thereby influencing the availability of natural lighting within the interior space.

Subsequently, the date and time settings were configured in VELUX Daylight Visualizer for the natural lighting analysis. Natural lighting was evaluated through simulations under various weather conditions and times throughout the year [18]. The selected representative dates corresponding to different annual solar positions were March 21 and December 21, with simulations conducted at 09:00, 12:00, and 15:00. These observation times were chosen to provide a representative assessment of variations in natural lighting intensity [19].

Development and Evaluation of Opening Design Strategies

The subsequent stage involved developing opening design strategies, including adjustments to window dimensions, the addition of shading elements, and the integration of corridor skylights. These design modifications were then re-evaluated through simulation to assess improvements in daylighting performance. Natural lighting performance depends greatly on appropriately designed openings. An ideal Window-to-Floor Ratio (WFR) is generally greater than 20% to satisfy visual comfort and productivity

requirements. However, in practice, constraints such as limited space, building orientation, and external obstructions often prevent windows alone from providing sufficient natural lighting to achieve this target [12][15].

To address these limitations, the incorporation of skylights can serve as an effective strategy for enhancing natural lighting from the upper portion of the building. A skylight is a roof opening fitted with glazing that allows natural daylight to penetrate the interior space [16][17]. Because daylight enters directly through the roof, skylights help distribute light more uniformly throughout the space while reducing dependence on artificial lighting (Figure 4).

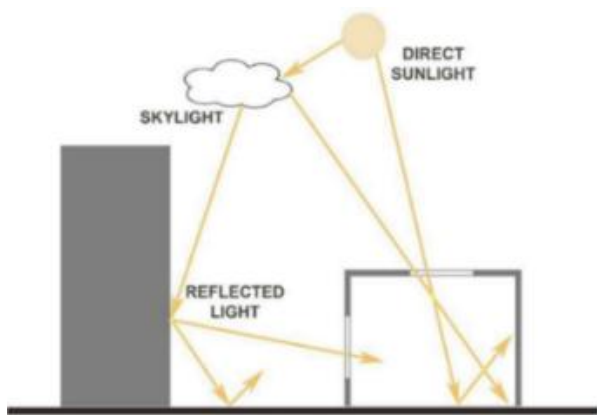


Figure 4. Illustration of the Effect of Skylight Reflectance on Indoor Natural Lighting (Source: Modaresnezhad, 2017).

Results

Initial Design Analysis

The simulation results of the initial classroom design were analyzed by considering the characteristics of the building openings. The classroom contains a total of three Type A window frames and one Type B window frame (Figure 5). These openings are positioned at a height of 0.90 m above the finished floor level. The classroom has a floor area of 56 m². Based on the standard Window-to-Floor Ratio (WFR), the window area should exceed 20% of the floor area. Accordingly, the required minimum opening area is 11.2 m², which serves as the reference value for this classroom. The total glazed area of all openings is 11.83 m², indicating that the WFR of the initial opening design complies with the required standard.

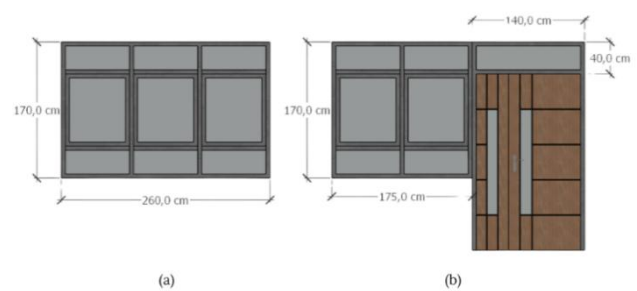


Figure 5. Window Dimensions in the Initial Opening Design of the SD Labschool UPI Building.

The floor plan and axonometric view (Figure 6) illustrate the distribution of the windows along the classroom walls. The arrangement of the students' desks and chairs faces the wall without openings. The axonometric view also shows architectural elements on the facade, including roof overhangs and projecting walls on the second-floor classrooms. These elements function as protection against direct sunlight [20].

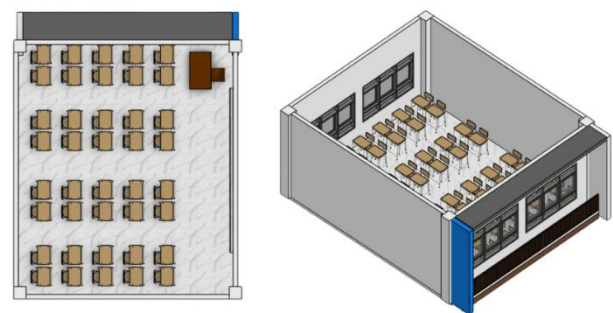


Figure 6. Floor Plan and Axonometric View of the SD Labschool UPI Classroom.

Although the facade incorporates architectural elements that provide protection from direct solar radiation, the daylight analysis indicates that the incoming daylight is primarily concentrated near the front facade. This condition may result in glare that compromises visual comfort when there is a significant contrast between the opening areas receiving direct sunlight and the rest of the interior space.

Furthermore, the simulation visualizations generated using VELUX demonstrate that daylight distribution within the classroom is relatively uneven. The daylight simulations were conducted on representative dates commonly used in daylighting analysis. In general, simulations are performed during the spring equinox, when the sun is positioned directly above the equator and the durations of day and night are nearly equal. In addition, the winter solstice is commonly used as a reference condition for daylighting analysis, as it

represents the shortest daylight period and the longest night of the year [21].

March 21 represents the spring equinox, while December 21 represents the winter solstice [22]. On each date, simulations were conducted at three observation times, namely 09:00, 12:00, and 15:00, which are presented sequentially from left to right in the figures (Figures 7 and 8).

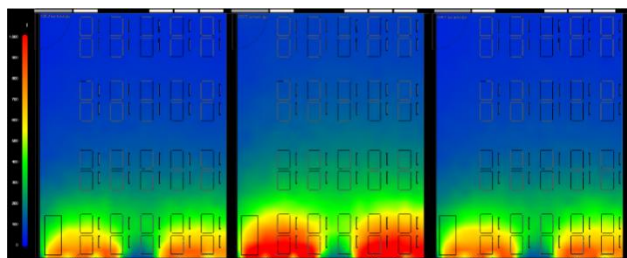


Figure 7. VELUX Simulation Results for March 21 Based on the Initial Design of the First and Second Floors.

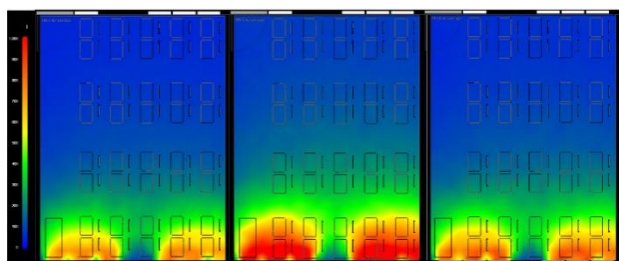


Figure 8. VELUX Simulation Results for December 21 Based on the Initial Design of the First and Second Floors.

The scale shown on the left side of the figures (Figures 7 and 8) represents the illuminance level in lux, ranging from a minimum of 0 lux (dark blue) to a maximum of 1000 lux (red). In these simulation visualizations, areas colored blue to cyan indicate illuminance levels of approximately 200 lux, while green to yellowish-green areas represent illuminance levels between 300 and 500 lux. The initial design simulation is predominantly characterized by blue-colored areas. Yellow and orange regions are also observed near the front facade openings, indicating illuminance levels ranging from approximately 600 to 800 lux.

The simulation results indicate that the average illuminance received by the classroom on March 21 across the three observation times was 299.4 lux (Figure 7), while on December 21 it reached only 256.5 lux (Figure 8). These values remain below the required standard of 350 lux, which is the minimum illuminance level for optimal classroom lighting. These findings are consistent with previous studies reporting that most classrooms in Indonesia have not yet achieved the minimum illuminance standard, as well as other studies that identified inadequate light

intensity and uneven daylight distribution within classrooms [4],[5],[8].

The low illuminance levels reported in previous studies indicate that the utilization of natural lighting in educational buildings remains suboptimal. These findings highlight the need for more strategic design approaches to improve both the penetration and distribution of daylight within interior spaces. Based on these findings, this study developed and evaluated facade opening design strategies together with the integration of skylights to achieve more uniform daylight distribution while complying with visual comfort standards.

Proposed Design Analysis

On the first-floor facade, the window opening configuration was modified to enhance daylight penetration into the classrooms (Figure 9a). This modification was implemented in response to the addition of external shading elements so that, despite the presence of shading devices, sufficient daylight could still enter the classrooms with a more uniform distribution. Each window module is equipped with a top-hung opening system, allowing the window sash to tilt outward while simultaneously functioning as a daylight control and natural ventilation element.

Previous studies have demonstrated that only certain opening configurations and window-to-wall ratio (WWR) values are capable of meeting the required illuminance standards, indicating that daylighting performance largely depends on window proportions and geometry [6]. This configuration allows daylight to enter the space in a diffused manner through the window openings while reducing direct solar radiation that may cause glare. In this study, the total facade opening area was designed to satisfy the recommended WWR, enabling all classrooms to achieve the required illuminance level more consistently.

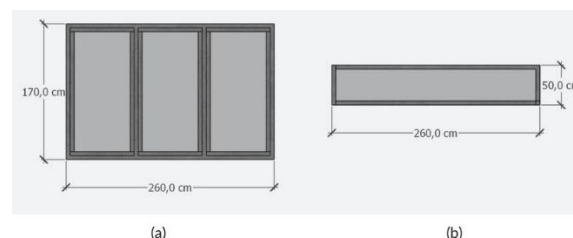


Figure 9. Main Window Dimensions of the Proposed Second-Floor Facade Design for Phase II SD Labschool UPI.

The window opening configuration on both the first and second floors was modified to enhance daylight penetration into the classrooms (Figure 9a). In

addition, an auxiliary opening in the form of a clerestory window was introduced above the main window plane (Figure 9b). A clerestory window is a horizontal opening positioned at the upper part of a wall, near the ceiling or roof, which functions to admit indirect natural light deeper into the interior by reflecting daylight off the ceiling, thereby producing a more uniform light distribution and reducing the potential for direct glare [23]. The presence of this indirect daylight opening, which subsequently reflects light onto the ceiling surface, contributes to increasing the illuminance level while improving the uniformity of daylight distribution within the classroom. The combination of enlarging the main openings and incorporating clerestory windows is expected to enhance the quality of natural lighting without creating excessive lighting contrast.

To reduce the potential for glare near the front facade of the first floor, louvres were added (Figure 10), while the second floor was equipped with a timber louvered secondary skin (Figure 11). These elements function as light-filtering and light-directing devices, enabling better control of the intensity of direct solar radiation entering the interior while producing a more diffused daylight distribution. With the incorporation of these shading elements, illuminance contrast near the openings can be reduced, thereby improving the visual comfort of the occupants.



Figure 10. Dimensions of the Timber Louvered Secondary Skin Panels in the Proposed Design for the Phase II SD Labschool UPI Building.



Figure 11. Dimensions of the Timber Louvered Secondary Skin Panels in the Proposed Design for the Phase II SD Labschool UPI Building.

In the subsequent design development stage, a skylight was incorporated into the second-floor corridor, which serves as a connecting space between the classrooms and the surrounding rooms. The addition of the skylight aims to improve the distribution of natural lighting within the corridor, thereby allowing daylight to be reflected through the surrounding windows and glazed surfaces. Furthermore, most previous studies have focused on optimizing facade openings or integrating artificial lighting, while the use of roof elements such as skylights as a source of indirect daylight has received limited attention [4],[5],[6],[7],[8]. Therefore, the integration of a corridor skylight in this study provides a novel approach to enhancing the penetration and uniform distribution of natural daylight.

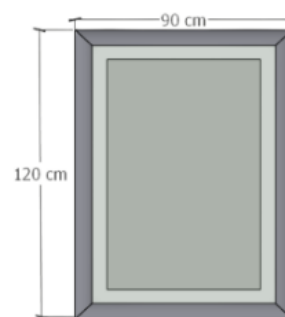


Figure 12. Skylight Dimensions for the Corridor Roof Area in the Proposed Design for Phase II SD Labschool UPI.

The skylight dimensions are 120 × 90 cm (Figure 12), with a total glazed area of 2.64 m². The skylight utilizes Clear Low-E glass, which is coated with a special low-emissivity layer designed to reduce ultraviolet (UV) heat gain [24]. Meanwhile, the window frames on the first and second-floor facades (Figures 5 and 10) use Clear Float glass, a standard clear glazing material with high visible light transmittance (Table 3) [25].

Table 3. Optical Properties of the Glass Materials Used in the Proposed Design

No.	Type of Glass	Transmittance	Reflectance Out	Reflectance In
1	Clear Float	79%	44%	13%
2	Clear Low-E	62%	11%	12%

The comparative axonometric views before and after the implementation of the proposed design illustrate a significant transformation of the building facade (Figure 13). These modifications include the addition of skylights on the roof as a source of indirect natural lighting, the enlargement of window openings to enhance daylight penetration, and the integration of a

secondary skin and external shading devices to control solar radiation. The combination of these strategies demonstrates a shift in the design approach from a passive facade to one that is more responsive to the optimization of natural lighting.

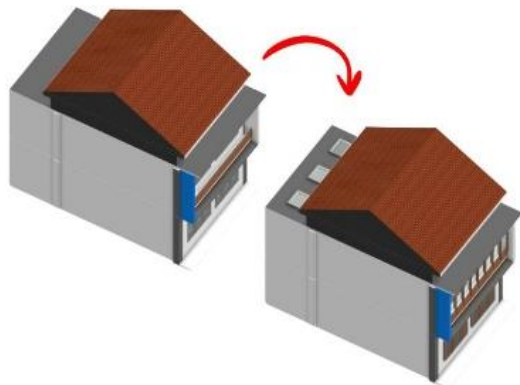


Figure 13. Louvre Dimensions on the Proposed Second-Floor Façade Design for Phase II SD Labschool UPI.

Testing of the proposed design on the first floor demonstrated an improvement in natural lighting performance, achieving average illuminance values of 350.3 lux on March 21 (Figure 14) and 358.6 lux on December 21 (Figure 15). On the second floor, the average illuminance reached 362.5 lux on March 21 (Figure 16) and 352 lux on December 21 (Figure 17). These results represent a significant improvement compared with previous studies, which reported that the majority of classrooms remained below the required illuminance standard due to limited openings, uneven daylight distribution, or dependence on artificial lighting [2][3][4].

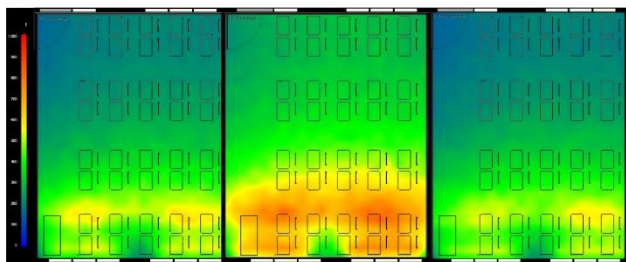


Figure 14. VELUX Simulation Results for March 21 Based on the Proposed First-Floor Design.

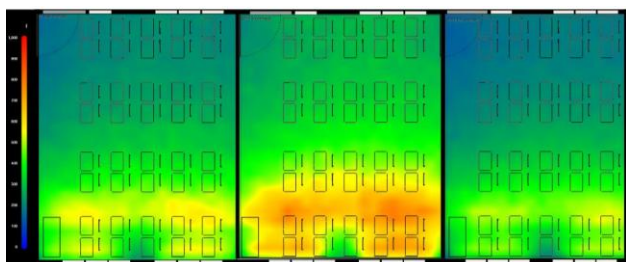


Figure 15. VELUX Simulation Results for December 21 Based on the Proposed First-Floor Design.

In the simulation visualizations of the proposed design, areas with low illuminance (indicated by blue) were significantly reduced and replaced by green to yellowish-green areas, representing illuminance levels ranging from 300 to 500 lux. This indicates that natural daylight distribution became more uniform throughout the classroom. Yellow and orange areas, representing higher illuminance levels of approximately 600–800 lux, appeared only in zones adjacent to the openings. These values fall within the illuminance range recommended for learning activities by the *IESNA Lighting Handbook*, which specifies 500–800 lux for visual tasks requiring a moderate level of precision [14]. The relatively high illuminance in these areas does not necessarily result in glare, as glare is more strongly influenced by the non-uniformity of light distribution and the contrast in illuminance levels than by high illuminance alone [2].

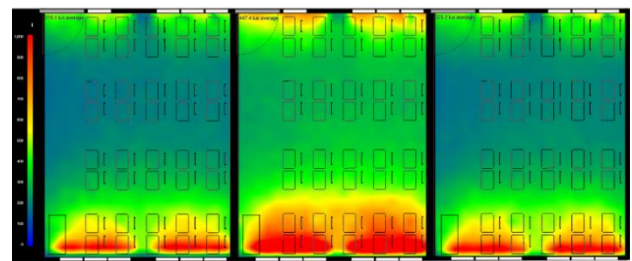


Figure 16. VELUX Simulation Results for March 21 Based on the Proposed Second-Floor Design.

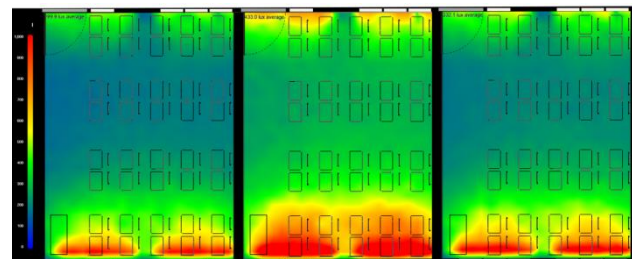


Figure 17. VELUX Simulation Results for December 21 Based on the Proposed Second-Floor Design.

Discussion

Although the proposed design satisfies the minimum illuminance standard, the daylight distribution within the classroom is not yet completely uniform. Areas with higher illuminance levels, ranging from approximately 600 to 800 lux, remain concentrated near the openings. These values are still within the recommended range for learning activities requiring a moderate level of visual precision and therefore do not directly compromise visual comfort. Nevertheless, this condition indicates that the quality of natural lighting is determined not only by the illuminance level but also by the uniformity of light distribution

throughout the space. This finding is consistent with previous studies on daylight comfort in educational buildings, which reported that spaces with adequate illuminance are not necessarily optimal if daylight is unevenly distributed across the working plane [5], [9]. Therefore, natural lighting strategies should be designed not only to satisfy illuminance standards but also to direct and distribute daylight more evenly in order to enhance visual comfort.

The findings of this study are also consistent with previous research on the influence of opening design on natural lighting, which demonstrated that the size, position, orientation, and geometry of openings play a crucial role in determining the quality of daylight within classrooms [6]. In this study, the combined strategy of integrating the main openings, corridor skylights, louvres, and a secondary skin demonstrates that improved daylight performance can be achieved through the interaction of multiple architectural elements rather than by simply enlarging the openings. From a theoretical perspective, these findings reinforce the view that natural lighting performance in educational buildings results from the interaction between facade configuration, daylight entry paths, and solar radiation control, rather than from any single design element.

The findings regarding the importance of daylight uniformity are also consistent with studies highlighting the influence of surface reflectance on natural lighting quality [7]. Surfaces with higher reflectance help redirect daylight deeper into the interior, thereby reducing excessive contrast between brightly illuminated and darker areas. In this context, the differences in daylight distribution observed between the first and second floors demonstrate that, in addition to the openings, interior material characteristics and reflective surfaces also contribute significantly to daylight performance. This suggests that achieving adequate illuminance should be accompanied by appropriate consideration of reflectance properties and spatial composition to ensure that daylight is distributed more effectively throughout the space.

When compared with previous studies reporting the limitations of natural lighting in educational buildings in Indonesia, such as those conducted in the coastal region of South Sulawesi and in Makassar [4], [5], the findings of this study present a more encouraging outcome, as the proposed passive design strategies successfully increased illuminance levels beyond the required standard. However, this study also demonstrates that achieving the minimum illuminance

threshold alone is insufficient, as the quality of daylight distribution remains an important consideration. In other words, this research extends the discussion beyond the question of whether a classroom is sufficiently illuminated to how daylight should be distributed within the space to effectively support visual comfort during learning activities.

Furthermore, the use of simulation during the early design stage provides an additional theoretical contribution compared with previous studies that primarily focused on evaluating existing buildings through post-occupancy assessment [4], [8], [9]. Through simulation, design strategies can be evaluated before construction, enabling design decisions to be more preventive and performance-based. This demonstrates that natural lighting optimization can be incorporated as an integral part of the sustainable design process rather than being limited to a post-construction evaluation.

Conclusion

This study aimed to evaluate the compliance of the facade and opening design of classrooms at SD Labschool UPI with natural lighting standards and to formulate more effective design improvement strategies. The findings indicate that the initial design did not satisfy the minimum illuminance requirement of 350 lux. The proposed design, which combines corridor skylights, optimized openings, and a secondary skin, successfully improved daylight performance beyond the required standard. Overall, the findings demonstrate that responsive facade and roof design strategies can provide an effective approach to improving the quality of natural lighting in educational buildings.

From a broader perspective, this study demonstrates that optimizing natural lighting is not merely a matter of meeting the required illuminance level but also of achieving more uniform daylight distribution, reducing dependence on electrical energy, and enhancing the visual comfort of building occupants. Theoretically, these findings suggest that daylighting in school buildings should be understood as an integrated system involving openings, orientation, materials, shading devices, and roof elements. Practically, the results of this study may serve as a reference for designers of elementary educational buildings in developing facades that are more responsive to climatic conditions and learning requirements.

The limitations of this study include the use of digital simulation without validation through on-site measurements and the absence of a quantitative glare analysis. Future studies are therefore recommended to conduct field validation, incorporate quantitative glare assessments, and investigate variations in material properties and shading configurations to develop more comprehensive and effective natural lighting strategies.

AI Use Declaration

The authors acknowledge the use of ChatGPT-5.5 (OpenAI) during the preparation of this manuscript to assist with translation from Indonesian into English, grammar checking, language editing, and improving the clarity and readability of the text. Typical prompts included: "*Translate this text into academic English while preserving the original meaning and technical terminology,*" and "*Proofread and improve the grammar, clarity, and academic writing style without changing the scientific content.*"

The AI tool was used solely for language assistance and was not used for content generation, image creation, data analysis or interpretation, or drawing conclusions. All AI-assisted outputs were carefully reviewed, verified, and revised by the authors before being incorporated into the manuscript. The authors take full responsibility for the accuracy, originality, and integrity of the content of this manuscript. Funding.

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