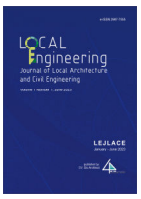
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Architecture – Research Article

Evaluation of Daylighting Performance in a Heritage Javanese House Adapted as an Inclusive School

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A B S T R A C T

The conversion of heritage buildings from residential to educational use presents challenges for lighting performance, as the existing spatial layouts and window openings were not originally designed for learning activities, while physical modifications are restricted by conservation principles. This quantitative study applies a performance-based evaluation approach to assess illuminance levels, uniformity, and spatial and temporal distribution in six classrooms at SD Tumbuh 3, located within the Dalem Mangkubumen heritage complex. Field measurements were conducted using a lux meter at 25 grid points in each classroom at one-hour intervals under daylight-only conditions. The data were analyzed based on average illuminance (Eavg), uniformity, and light distribution patterns, using the 350-lux classroom illuminance requirement specified in SNI 6197:2020 as a reference. The results show that average daylight illuminance failed to meet the 350-lux requirement in 36 of the 42 classroom-session observations. Of the 1,050 point-time readings, 90.67% were below 350 lux, while only 9.33% reached or exceeded this threshold. The findings also indicate that high average illuminance does not necessarily correspond to adequate uniformity and spatial coverage. These results provide an empirical basis for developing lighting improvement strategies that address educational needs while respecting the conservation constraints of heritage buildings.

INTRODUCTION

Adaptive reuse, as a conservation strategy, focuses on the sustainable utilization of existing buildings to accommodate new functions without compromising their inherited historical values (Plevoets and Cleempoel 2019; Arfa et al. 2022). The performance requirements of interior spaces change in proportion to their functional transformation; consequently, pre- and post-conversion evaluations constitute one of the indicators of adaptive reuse success (Vafaie, Remøy, and Gruis 2023). One important aspect of spatial performance that requires evaluation is natural lighting (daylighting), as it supports the visual requirements of occupants during various activities and influences the quality of the indoor visual environment (Baker and Steemers 2002; Ramos 2019). In heritage buildings, preserved architectural characteristics can influence the capacity of interior spaces to receive and distribute natural light. Accordingly, Sönmez and Cilasun Kunduraci (2026) emphasize that strategies for improving daylighting in historic buildings must consider architectural integrity, the reversibility of interventions, and compatibility with conservation values.

Daylighting performance is shaped by the relationship between site-specific lighting conditions and building characteristics. The dimensions, positions, and configurations of openings regulate the amount of light entering a building. Spatial forms, orientations, and layouts determine the potential depth to which daylight can penetrate the interior. Obstructions and shading elements may restrict access to skylight, while surface reflectance also determines the distribution patterns of light within a space (Baker and Steemers 2002). Through measurements of natural lighting in typical residential buildings in Semarang, Gunawan and Dwiyanto (2023) identified differences in illuminance levels based on building positions and measurement times, with lower light reception in attached housing units than in detached houses with the same orientation. In their study of classrooms in tropical buildings, Mangkuto and Bintoro (2025) found that shading depth and elevation exerted significant influences on daylighting

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performance, whereas the distance between obstructing buildings demonstrated a relatively minor influence in the simulations they examined.

In historic buildings, similar issues have received particular attention from Susan and Prihatmanti (2017), who investigated daylight characteristics in classrooms at two secondary schools occupying heritage buildings in Surabaya. Their research combined illuminance measurements at the working plane, daylight factor assessments, uniformity indices, and observations of the surrounding environment. The results indicated that natural illuminance levels in the investigated spaces remained low, with the highest recorded value reaching only 105 lux and uniformity indices ranging from 0.33 to 0.36. Although both buildings possessed architectural elements that theoretically supported light penetration, the presence of corridors and surrounding buildings restricted access to light from the external environment. These findings demonstrate that architectural strategies with the potential to support daylighting do not necessarily produce adequate illuminance levels when the availability of light sources and surrounding environmental conditions are unfavorable Susan and Prihatmanti (2017).

In educational facilities, lighting constitutes an essential component of indoor health and comfort requirements (New Zealand Ministry of Education 2020). Activities such as reading, writing, and observing learning objects require lighting conditions that provide adequate visibility of visual objects at the working plane (Badan Standardisasi Nasional 2020). The importance of providing learning environments that accommodate the diversity of students is further reinforced by Permendikbudristek Number 48 of 2023 concerning reasonable accommodations for students with disabilities. Research by Ming En et al. (2026) indicates that lighting requirements in learning environments for autistic children may vary depending on their visual and sensory sensitivities. In the context of inclusive schools, this condition highlights the importance of flexible visual environments. Evaluating illuminance levels and their distribution therefore constitutes an initial step toward understanding the capacity of a space to provide lighting conditions that accommodate the diverse needs of its users.

These issues are particularly relevant to Dalem Mangkubumen in Yogyakarta, a former aristocratic residential complex that has undergone functional transformation into an educational facility. Widya Mataram University occupies several of the principal buildings, while SD Tumbuh 3 utilizes the left-wing section (gandhok kiwa). Previous studies of the Dalem Mangkubumen complex have extensively examined its architectural history, functional and spatial transformations, and structural characteristics (Yuniastuti, Wibowo, and Sukirman 2014; Adianti, Ikaputra, and Rahmi 2024; Wismantoro and Yuniastuti 2022). Ayuningtyas, Adianti, and Kindi (2025) evaluated the visual comfort of office spaces at Widya Mataram University, located in Gedhong Hinggil, and their measurement results indicated that the average illuminance levels remained below the applicable standards. Meanwhile, no comparable study focusing on the classrooms at SD Tumbuh 3 has been identified. As an inclusive school, evaluating its daylighting performance requires a distinct analytical approach, considering the building's historical characteristics and its previous spatial functions, which were not originally intended to accommodate learning activities.

Lighting requirements in residential buildings and educational facilities differ according to the types of activities performed within their respective spaces. The Green Building Council Indonesia (GBC Indonesia 2014) employs a daylighting benchmark requiring at least 30% of the floor area used for work activities to receive natural illuminance of at least 300 lux. This distinction is also reflected in geometric guidelines for building openings. Neufert (1996) states that the minimum glazed opening area for residential living spaces should equal 1/8 of the floor area, corresponding to a window-to-floor ratio (WFR) of 12.5%. Similarly, Ministerial Decree of the Minister of Human Settlements and Regional Infrastructure Number 403/KPTS/M/2002 establishes a minimum light-opening area of 10% of the floor area as one of the design guidelines for healthy simple housing. Tregenza and Wilson (2011) provide a historical summary of WFR values ranging from 8% to 13% for residential buildings and 17% to 25% for schools. Meanwhile, Kalaimathy et al. (2023) found that a window-to-wall ratio (WWR) of 16% could satisfy daylighting performance criteria in the hot-humid residential building model examined in their study. In comparison, the New Zealand Ministry of Education (2022), in its Designing Quality Learning Spaces document, establishes a WWR of 20%–35% of the external wall area as a design requirement for learning spaces, taking natural lighting and thermal comfort into consideration.

Table 1. Minimum WWR thresholds according to room depth

No	Room Depth	Minimum WWR
1	< 8 meters	20%
2	8-11 meters	25%
3	11-14 meters	30%
4	> 14 meters	35%

Source: New Zealand Ministry of Education 2020

These differences in reference criteria indicate that opening configurations inherited from residential functions cannot automatically be considered suitable for the lighting requirements of educational facilities. SD Tumbuh occupies gandhok kiwa, which was originally used as a warehouse and sleeping quarters. SNI 6197:2020 establishes a minimum average illuminance of 50 lux for warehouses and bedrooms, whereas classrooms require 350 lux (Badan Standardisasi Nasional 2020). Consistent with this requirement, Minister of Public Works and Housing Regulation Number 21 of 2021, concerning green building provisions, states that artificial lighting should be used when natural lighting cannot achieve the required minimum illuminance level. Permendikbudristek Number 22 of 2023 stipulates that educational spaces should prioritize the utilization of natural lighting. Therefore, measuring existing daylighting conditions is necessary to evaluate the

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performance of the existing spaces in accommodating the requirements of their new functions.

An evaluation based solely on average illuminance measurements does not fully indicate the proportion of the working plane receiving natural light at a particular illuminance level and time. In response to this issue, this study aims to evaluate illuminance levels, daylighting area coverage, and spatial and temporal distribution in six classrooms at SD Tumbuh 3 within the Dalem Mangkubumen complex, while also identifying performance variations between classrooms and observation sessions. These variations are subsequently interpreted descriptively by considering opening characteristics and environmental conditions based on the principles established by Baker and Steemers (2002). Accordingly, this study is expected to provide an empirical overview of daylighting performance and its variations in a historic building that has been repurposed as an inclusive educational facility.

RESEARCH METHODS

This study employs a quantitative approach using field measurement methods to evaluate the actual illuminance performance of classrooms. A quantitative approach positions variable measurement and numerical data analysis as the basis for empirical verification, while architectural research strategies align empirical evidence with the research questions (Creswell and Creswell 2023; Groat and Wang 2013). The primary variable measured was horizontal illuminance at the working plane (lux), with the following evaluation indicators: Eavg, Emed, U_o, P_{350}, S_{350}, and P_{300}. Supporting parameters for interpretation included WWR, WFR, spatial characteristics, openings, and environmental conditions. The evaluation framework adapted the principles of performance-based evaluation through the establishment of performance objectives, measurable indicators, data collection procedures, and criteria for interpreting results (Konis and Selkowitz 2017).

The research was conducted at SD Tumbuh 3, which occupies part of the Dalem Mangkubumen heritage complex in Yogyakarta as an educational facility resulting from adaptive reuse. Field measurements were conducted on September 12, 2026, a date close to the equinox phase, when Earth's rotational axis is neither tilted toward nor away from the Sun, resulting in relatively balanced solar exposure between the Northern and Southern Hemispheres. Architectural documentation involved measuring room dimensions, floor areas, the number and orientation of openings, and the environmental boundary conditions of each classroom. Environmental documentation included the configurations of corridors and covered walkways, roof overhangs, courtyards, and the presence of adjacent spaces or buildings near the openings. This information served as the basis for interpreting daylight access and distribution according to the principles of natural light reception and distribution proposed by Baker and Steemers (2002).



Figure 1. Front Façade of SD Tumbuh 3



Figure 2. Classroom 1 (Lower A)

Natural illuminance measurements were conducted across seven sessions during school operating hours, from 08:00 to 14:00, with measurements repeated at one-hour intervals. The units of analysis comprised all elementary-level classrooms: Lower A, Middle A, Upper A, Upper B, Lower B, and Middle B, using total sampling. The measurement procedures and determination of measurement points followed the principles for measuring lighting intensity specified in SNI 7062:2019, together with Amendment 1:2020, which differentiates the number of general lighting measurement points according to room area:

- Rooms < 50 m²: one measurement point represents every 3 m².
- Room areas of 50–100 m²: a minimum of 25 measurement points.
- Room areas > 100 m²: a minimum of 36 measurement points.

Based on these provisions, all six classrooms, each with an area ranging from 54.23 to 61 m², were measured using 25 measurement points (Badan Standardisasi Nasional 2019; 2020).

Table 2. Number of measurement points and distances between points

Classroom	Room dimensions (m)	Area (m²)	Number of points	Distance between points (m)
Lower A	8,13 x 6,67	54,23	25	1,3 × 1,6
Lower B	8,63 x 6,70	57,85	25	1,3 × 1,7
Middle A	8,57 x 6,71	57,55	25	1,3 × 1,7
Middle B	9,05 x 6,71	60,79	25	1,3 × 1,8
Upper A	9,11 x 6,69	61,00	25	1,3 × 1,8
Upper B	8,54 x 6,69	57,17	25	1,3 × 1,7

The instruments used consisted of three Smart Sensor AS803 digital lux meters, each with a measurement range of 1–200,000 lux, a resolution of 1 lux, nominal accuracy of ±5% of the reading ±10 digits, and measurement repeatability of ±2%. Each field measurement operator was responsible for two classrooms and used the same assigned instrument throughout the measurement activities. Each measurement sequence in an individual classroom consisted of 25 points and took approximately 1.5 minutes. The reading duration was kept relatively short to minimize changes in lighting conditions during each measurement session. Measurement preparation was carried out one day before data collection (D−1), when the author marked all measurement points in the six classrooms according to the predetermined grid arrangement.

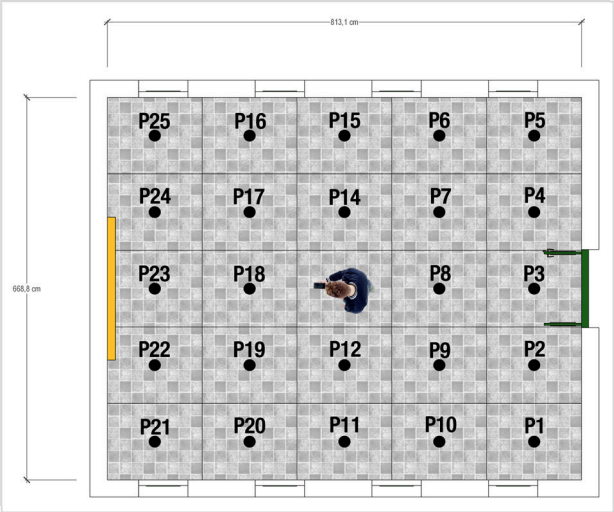


Figure 3. Example of measurement point grid (Lower A)

Subsequently, a measurement guideline was prepared to standardize sensor positioning, the orientation of field operators, reading sequences, data recording, and documentation procedures. On the measurement day, the author ensured that all windows remained open and all artificial lights were switched off to isolate the contribution of natural lighting. Instructions were provided to the measurement operators before data collection began to ensure that all procedures were understood and implemented consistently. The field measurement procedures consisted of the following stages:

1. Measurement of external lighting conditions. Before beginning measurements in each classroom, the operator recorded horizontal outdoor illuminance at an unobstructed location (open-sky condition) to document the lighting conditions of the natural light source.
2. Inspection of room conditions. The operator reconfirmed that all windows were open and all artificial lights were switched off.
3. Sensor placement and data recording. The lux meter sensor was positioned horizontally at working-plane height (75 cm above the floor). The lux meter was held in the operator's left hand, while a mobile phone was held in the right hand to document the measurement readings. Measurements were taken sequentially following a serpentine pattern, from the first point to the twenty-fifth point, according to the predetermined guidelines. During documentation, the position of the mobile phone was maintained to ensure that it did not cast a shadow over the sensor.
4. Control of operator positioning. The guidelines specified that operators must face east or west so that their bodies would not cast shadows over the light source or sensor. The orientation of the instrument was maintained toward the whiteboard, with the sensor surface remaining horizontal.
5. Repeated measurements. All procedures, measurement point positions, operator orientations, reading sequences, and window and lighting conditions were maintained consistently throughout subsequent measurement sessions.

With six classrooms, 25 measurement points, and seven observation sessions, a total of 1,050 illuminance readings were obtained as the basis for evaluating daylighting performance. Illuminance performance was evaluated using six indicators, with the following equations:

1. Average illuminance (Eavg) was calculated by summing the illuminance values at all 25 measurement points and dividing the result by the total number of measurement points.
   $$E_{avg} = \frac{\sum E_i}{n}$$
2. Median illuminance (Emed) was obtained from the median of all readings recorded during each session.
   $$E_{med} = median(E_1, E_2, \ldots, E_n)$$
3. Uniformity index (U_o) was calculated by dividing the minimum illuminance by the average illuminance within a single measurement session.
   $$U_0 = \frac{E_{min}}{E_{avg}}$$
4. P350 represents the percentage of measurement points with illuminance levels ≥350 lux.
   $$P_{350} = \frac{n_{350}}{n} \times 100\%$$
5. The S350 indicator represents the proportion of observation sessions in which the average classroom illuminance (Eavg) reaches or exceeds 350 lux. It is calculated by dividing the number of qualifying sessions by the total number of observation sessions. In this study, S350 is reported as a fraction of the seven observed sessions, such as 5/7 or 1/7.
   $$S_{350} = \frac{t_{350}}{t}$$

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6. P300 was calculated as the percentage of measurement points with illuminance levels ≥300 lux relative to all 25 measurement points in each session, following the criteria established by GBCI.

$$P_{300} = \frac{n_{300}}{n} \times 100\%$$

The geometric characteristics of the openings were expressed through the following parameters:

1. Window-to-floor ratio (WFR) refers to the ratio of the total opening area to the floor area.

$$WFR = \frac{A_{openings}}{A_{floor}} \times 100\%$$

2. Window-to-wall ratio (WWR) refers to the ratio of the opening area to the analyzed wall surface area.

$$WWR = \frac{A_{openings}}{A_{wall}} \times 100\%$$

The analysis was conducted by comparing classrooms and measurement sessions to identify illuminance levels, the frequency of achieving the reference thresholds, and the proportion of the measurement plane receiving natural lighting. Temporal analysis was performed by examining changes in Eavg across the seven observation sessions, while spatial analysis employed illuminance distribution maps generated from the average of seven readings at each grid position. All maps used a north-oriented layout and consistent visualization scales to facilitate comparisons of patterns between classrooms. Contour maps were employed to illustrate the tendencies of spatial distribution based on the measurement points; therefore, the interpolated results were not considered additional field measurement data. Subsequently, the evaluation results were descriptively compared with the opening configurations and environmental characteristics of the spaces based on Baker and Steemers (2002).

RESULTS AND DISCUSSION

Spatial and environmental characteristics

The six classrooms at SD Tumbuh 3 exhibit different geometric characteristics and environmental conditions, as illustrated in figure 4 and table 3. Although they are located within the same building complex, each classroom has a different opening configuration and set of spatial boundary conditions. Lower A, Lower B, and Middle A are adjacent to an open covered walkway and an internal courtyard on their northern sides, while their southern sides have different shading configurations. Meanwhile, Middle B, Upper A, and Upper B have combinations of spatial boundaries consisting of enclosed corridors, semi-open covered walkways, roof overhangs, internal courtyards, and surrounding enclosed spaces. These differences in spatial characteristics provide the architectural context for evaluating variations in natural illuminance levels and distribution patterns in each classroom.

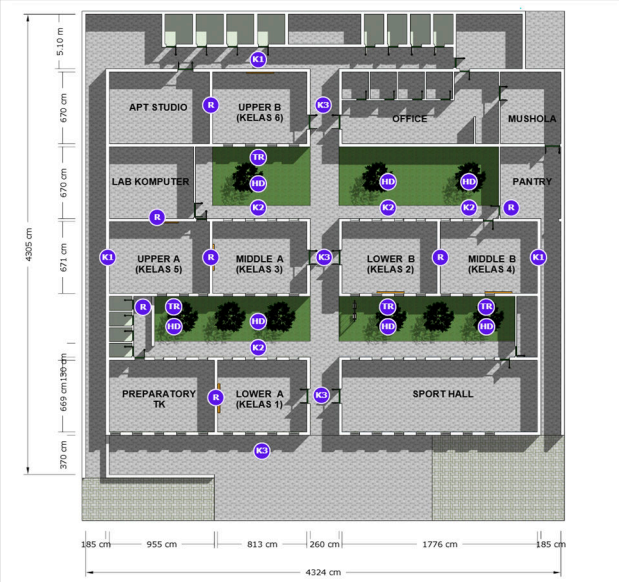


Figure 4. Floor plan of SD Tumbuh 3



Figure 5. Corridor



Figure 6. Courtyard

Table 3. Spatial boundaries

No	Boundary	Lower A	Lower B	Middle A	Middle B	Upper A	Upper B
1	West boundary	R	K3	R	R	K1	R
2	North boundary	K2+HD	K2+HD	K2+HD	K2+HD+R	R	K1
3	East boundary	K3	R	K3	K1	R	K3
4	South boundary	K3	TR+HD	TR+HD	TR+HD+R	TR+HD+R	TR+HD

Table 4. Spatial characteristics and their daylighting potential

Code	Description	Daylighting potential
K1	Enclosed corridor with a fully covered roof, relatively isolated from the external environment.	Limited access to skylight; daylight availability depends on corridor openings and potential reflected light.
K2	Open covered walkway with roof overhangs, directly connected to HD (Internal Courtyard).	Receives daylight from the open side, although some access to skylight is obstructed by the roof overhang.
K3	Semi-open connecting walkway with a fully covered roof, adjacent to an internal courtyard (HD).	Receives daylight through its open sides or at the ends of the walkway, while the roof restricts access to overhead light.
TR	Roof overhang attached to the building wall, without a covered walkway beneath it.	Restricts direct sunlight penetration and partially limits access to skylight through the openings.
HD	Internal courtyard located between building masses and open to the sky.	Has the potential to provide direct skylight and reflected light from courtyard surfaces and surrounding buildings.
HL	External yard located outside the configuration of the main building mass.	Provides access to skylight, with the degree of openness depending on surrounding obstructions.
R	Other enclosed spaces, including classrooms, kindergarten rooms, offices, or spaces serving other functions.	Does not provide direct access to the sky; daylight may be transmitted through connecting openings when available.
BL	Other buildings located around the observation spaces.	May obstruct skylight and direct sunlight while also contributing reflected light from their external surfaces.

Temporal analysis

The temporal graph demonstrates considerable variations in average daylight illuminance (Eavg) between classrooms and across observation times. Lower B recorded the highest Eavg, showing an increasing trend from 312.64 lux at 08:00 to a peak of 717.44 lux at 13:00, before decreasing to 682.16 lux at 14:00. Middle A reached its peak illuminance of 397.08 lux at 12:00, followed by a decline to 234.08 lux at 14:00. Meanwhile, Lower A, Middle B, Upper A, and Upper B consistently recorded average illuminance levels below 130 lux throughout the observation period.

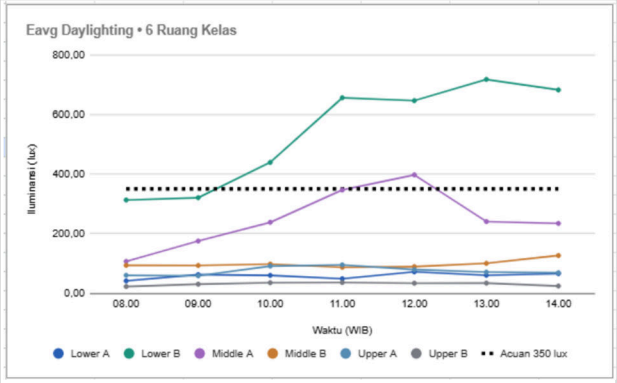


Figure 7. Temporal daylighting performance graph

Of the 42 classroom-session observations, only six sessions met the reference illuminance level of 350 lux. These comprised five sessions in Lower B, recorded between 10:00 a.m. and 2:00 p.m., and one session in Middle A, recorded at 12:00 p.m. This finding indicates that the contribution of daylighting to meeting classroom illuminance requirements can vary both temporally and spatially, with most measurement sessions failing to reach the adopted reference illuminance level (36 sessions recorded Eavg < 350 lux). The graph represents the average illuminance calculated from 25 measurement points in each classroom during each session; therefore, the illuminance received at individual measurement points may differ. This variation is closely related to light distribution across the working plane, which is examined further using the uniformity index (U_o) presented in the following table.

Table 5. Daylighting performance

No	Parameter	Lower A	Lower B	Middle A	Middle B	Upper A	Upper B
1	Eavg (lux)	58,4	539,09	248,16	98,07	74,61	30,67
2	Emed (lux)	56	77,71	46,57	41,71	23,86	7,86
3	U_o	0,617	0,104	0,109	0,194	0,15	0,14
4	P350 (%)	0	25,7	17,7	7,4	5,1	0
5	S350 (sesi)	0/7	5/7	1/7	0/7	0/7	0/7

A comparison of the indicators in table 5 demonstrates that higher average illuminance does not necessarily correspond to a more uniform distribution of light. Lower B recorded the highest seven-session average illuminance, at 539.09 lux; however, its median illuminance (Emed) was only 77.71 lux, with a uniformity index (U_o) of 0.104. A similar pattern was observed in Middle A, with an Eavg of 248.16 lux, an Emed of 46.57 lux, and a U_o of 0.109. In contrast, Lower A exhibited the highest uniformity (U_o = 0.617), with relatively similar Eavg and Emed values of 58.40 and 56.00 lux, respectively, although both remained substantially below the 350-lux reference level. The considerable differences between Eavg and Emed in Lower B and Middle A indicate that high illuminance values were concentrated at certain measurement points, thereby increasing the room average, while the median measurement value remained low. Accordingly, evaluating daylighting performance solely on the basis of Eavg is insufficient to describe the adequacy and uniformity of daylight distribution across the entire working plane. Emed complements Eavg by providing an

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indication of the central level of the illuminance distribution without being excessively influenced by extreme values.

Lighting uniformity was evaluated using the uniformity index (U_o), calculated as the ratio of minimum illuminance to average illuminance in each measurement session. A U_o value approaching 1 indicates a more uniform illuminance distribution, whereas a value approaching 0 indicates increasingly substantial differences in illuminance between measurement points. Lower B and Middle A recorded low U_o values of 0.104 and 0.109, respectively, indicating uneven light distribution despite having the highest Eavg values. Similar conditions were identified in Middle B, Upper A, and Upper B, with U_o values of 0.194, 0.150, and 0.140, respectively. Conversely, Lower A recorded the highest U_o value of 0.617, indicating a relatively more uniform distribution than that of the other classrooms. Nevertheless, its Eavg reached only 58.40 lux. These findings demonstrate that a uniform lighting distribution does not necessarily indicate an adequate illuminance level, while a room with high average illuminance does not necessarily have a uniform light distribution.

The P350 indicator was used to quantify the percentage of point-time illuminance readings reaching or exceeding 350 lux. Of the 1,050 point-time readings, only 98 (9.33%) reached ≥ 350 lux. Lower B recorded the highest P350 value, at 25.71%, followed by Middle A (17.71%), Middle B (7.43%), and Upper A (5.14%), while Lower A and Upper B had no measurement points that reached this threshold. Although Lower B recorded the highest Eavg, at 539.09 lux, only 45 of its 175 point-time readings met the reference illuminance level. This finding demonstrates that a high average illuminance does not necessarily mean that most locations across the working plane receive light at an equally high level. Thus, P350 indicates the proportion of measurement points that meet the reference illuminance level rather than the average lighting intensity of the room.

Unlike P350, which evaluates the proportion of measurement points meeting the reference level, S350 indicates the frequency of sessions in which a classroom's Eavg reached ≥ 350 lux. Lower B recorded the highest frequency, meeting the reference level in five of seven sessions between 10:00 a.m. and 2:00 p.m., whereas Middle A met the standard in only one session, at 12:00 p.m. Meanwhile, Lower A, Middle B, Upper A, and Upper B failed to reach the reference level in all measurement sessions. This difference indicates that Lower B achieved an average illuminance of 350 lux more frequently than the other classrooms. However, achieving the Eavg threshold in a particular session does not mean that all measurement points received an illuminance level of ≥ 350 lux. Accordingly, S350 describes how frequently the room average meets the reference illuminance level, whereas P350 indicates how many measurement points reach that threshold.

Spatial distribution patterns

Spatial distribution mapping was conducted to identify the areas with the highest and lowest illuminance levels in each classroom, characteristics that cannot be fully represented by the preceding quantitative indicators alone. Contour maps were generated using the average illuminance values from 25 measurement points across seven sessions to illustrate the general patterns of light distribution across the working plane. These patterns were subsequently examined in relation to the previously identified architectural characteristics, including the orientation and configuration of openings, shading elements, and surrounding environmental boundary conditions (table 3). Spatial mapping not only illustrates differences in illuminance levels between zones but also provides a basis for interpreting their possible relationships with the characteristics of each classroom. Accordingly, the spatial distribution patterns of the classrooms are presented sequentially to identify the measured characteristics of daylight penetration and reception.

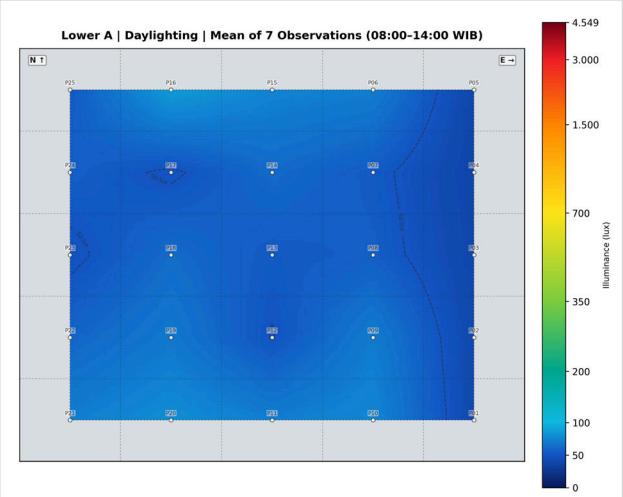


Figure 8. Light distribution in Lower A

Lower A exhibited a relatively uniform illuminance distribution, with slightly higher light concentrations in the western to central portions of the room (figure 8). This pattern is consistent with its highest uniformity index among the six classrooms (U_o = 0.617), although its average illuminance was only 58.40 lux. Based on the spatial characteristics presented in Figure 4, the northern opening faces an open walkway and an inner courtyard (K2+HD), whereas the southern side faces a fully roofed, semi-open walkway (K3). This configuration may restrict access to daylight from the southern opening, providing relevant context for understanding the low measured illuminance despite its relatively uniform distribution.

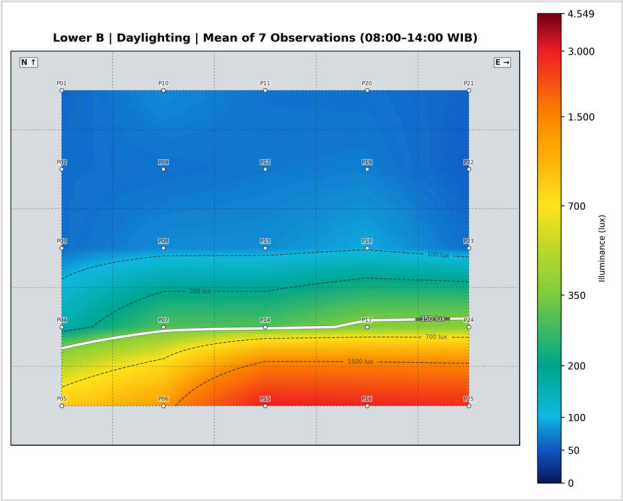


Figure 9. Light distribution in Lower B

Lower B exhibited a concentration of high illuminance in the southern portion of the room, particularly across the central to eastern zones, with a sharp decline toward the northern portion (figure 9). This pattern is reflected in its low uniformity index (U_o = 0.104), despite the classroom having the highest average illuminance. As shown in Figure 4, Lower B has the same number of openings on its northern and southern sides, with four louvered windows and four clerestory windows on each side. However, the northern side faces an open walkway (K2+HD), whereas the southern side faces an overhang and an inner courtyard (TR+HD). Differences in the environmental conditions immediately outside these openings may be associated with the unequal reception of daylight between the northern and southern portions of the room. Consequently, an equal number of openings does not necessarily result in a uniform illuminance distribution.

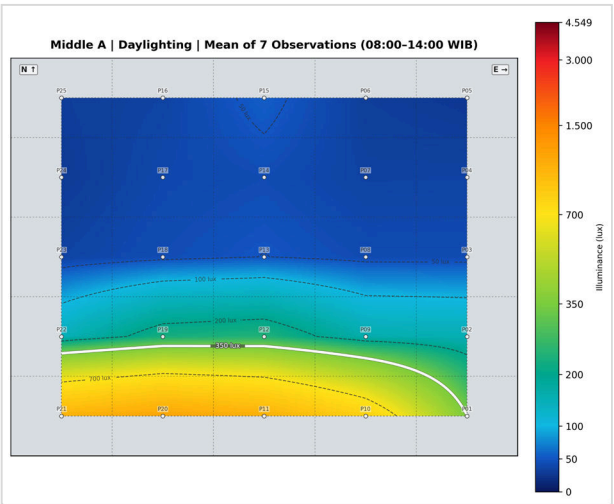


Figure 10. Light distribution in Middle A

Middle A exhibited a distribution pattern similar to that of Lower B, with the highest illuminance concentrated in the southern portion and decreasing toward the northern side (figure 10). Its U_o value of 0.109 indicates a low level of lighting uniformity. Interestingly, Middle A and Lower B have identical numbers and orientations of openings, accompanied by relatively similar boundary conditions on their northern (K2+HD) and southern (TR+HD) sides. Nevertheless, the two classrooms exhibit a considerable difference in average illuminance, measuring 248.16 lux in Middle A and 539.09 lux in Lower B. This finding suggests that even similar opening configurations may be associated with substantial differences in both illuminance distribution patterns and average illuminance levels. This represents an interesting finding for future research, particularly in reconsidering the limitations of geometric indicators in describing daylighting performance.

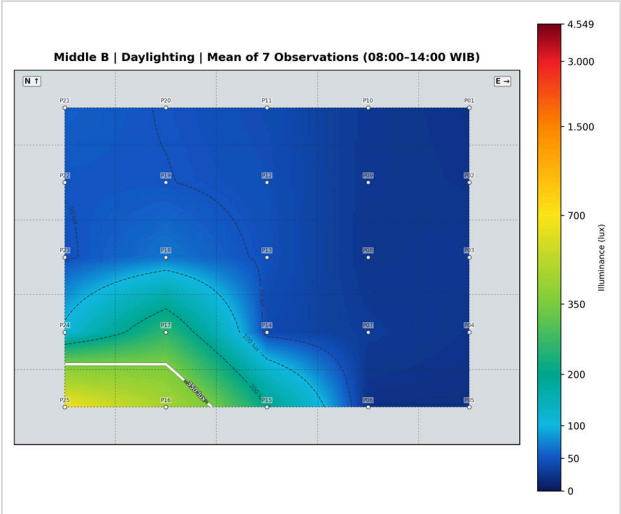


Figure 11. Light distribution in Middle B

Middle B exhibited a concentration of illuminance in the southwestern portion of the room, whereas the eastern and northern areas received relatively low levels of daylight (figure 11). This distribution is consistent with its U_o value of 0.194, indicating an uneven illuminance distribution across measurement points. Unlike the three previously discussed classrooms, Middle B has an asymmetrical opening configuration, with two louvered windows and two clerestory windows on the northern side, compared with three louvered windows and three clerestory windows on the southern side. In addition, one louvered window cannot be opened because the K1 area in that location is used for storage. This configuration provides relevant context for examining the limitations on light penetration into other parts of the room, together with other potential obstructive factors, including how users utilize the space.

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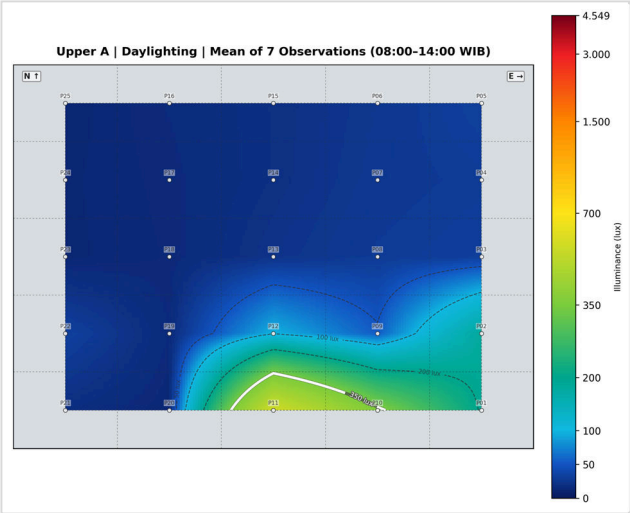


Figure 12. Light distribution in Upper A

Upper A exhibited concentrated illuminance in certain southern zones, particularly in the central to eastern portions of the room, while most of the measurement plane received low illuminance levels (figure 12). This pattern is consistent with its uniformity index of U_o = 0.150. Based on Figure 4, the room openings are located on the western and southern sides. However, the western side faces an enclosed corridor (K1), whereas the southern side faces an overhang, an inner courtyard, and an adjacent room (TR+HD+R). Differences in these boundary conditions may result in unequal access to daylight through the openings on the two sides and should therefore be considered when interpreting the concentration of illuminance in the southern zone.

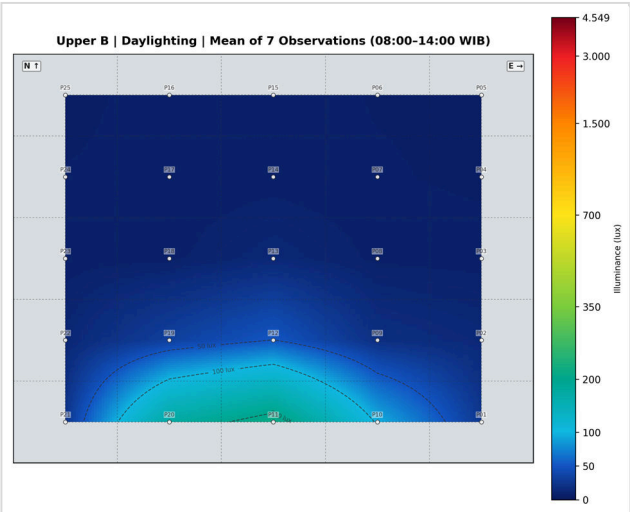


Figure 13. Light distribution in Upper B

Upper B exhibited relatively higher illuminance in the southern portion of the room, with a gradual decline toward the northern side (figure 13). Although its distribution pattern resembles those of several other classrooms, the overall illuminance level remained low, with a U_o value of 0.140. Based on its spatial characteristics, all window openings in Upper B face south and are adjacent to an overhang and an inner courtyard (TR+HD), whereas the northern side faces an enclosed corridor (K1). The concentration of openings along a single side is relevant to the observed pattern of higher daylight reception near the southern zone, which becomes increasingly limited toward the interior of the room.

Overall, the six classrooms exhibited variations in illuminance distribution associated with differences in their respective geometric characteristics and environmental conditions. Lower B and Middle A recorded high illuminance concentrated in the southern zones, accompanied by low uniformity values. Middle B, Upper A, and Upper B exhibited more localized concentrations of daylight, whereas Lower A demonstrated a relatively uniform distribution despite its low illuminance level. These differences indicate that illuminance uniformity and adequacy are two aspects of lighting performance that do not necessarily correspond. Furthermore, opening configurations and room boundary conditions provide a basis for examining the architectural characteristics of the six classrooms alongside potential obstructions, shading elements, and surrounding environmental conditions, in accordance with the daylighting principles discussed by Baker and Steemers (2002).

Table 6. Geometric characteristics of the classrooms

No	Parameter	Lower A	Lower B	Middle A	Middle B	Upper A	Upper B
1	Dimensions (m)	8,13 x 6,67	8,63 x 6,70	8,57 x 6,71	9,05 x 6,71	9,11 x 6,69	8,54 x 6,69
2	Area (m²)	54,23	57,85	57,55	60,79	61	57,17
3	WFR (%)	26,55	24,89	25,02	17,77	17,7	12,59
4	WWR (%)	15,06	14,41	14,47	11,91	14,21	11,33
5	Minimum P300 (m²)	16,26	17,35	17,26	18,23	18,3	17,151
6	Existing P300 0 (m²)		17,19	10,85	5,91	3,49	0,33
7	Existing P300 0 (%)		29,7	18,8	9,7	5,7	0,57

The calculations indicate that the WWR values of the six classrooms range from 11.33% to 15.06%, while their WFR values range from 12.59% to 26.55% (Table 6). As discussed in the Introduction, Neufert (1996) proposes a minimum daylight opening area equivalent to one-eighth of the floor area (12.5%) for residential sitting rooms, whereas Ministerial Decree of the Ministry of Settlements and Regional Infrastructure No. 403/KPTS/M/2002 stipulates a minimum light opening area of 10% of the floor area for healthy simple housing. Numerically, the WFR values of all the classrooms examined exceed both of these residential reference thresholds. However, this comparison indicates only nominal geometric adequacy in terms of opening-area proportions, rather than technical compliance with all residential lighting requirements. As a reference for educational buildings, historical literature on school design documents the use of WFR values ranging from 17% to 25%, while New Zealand's Designing Quality Learning Spaces guidelines discuss WWR in relation to room depth and the need for external views. These references indicate that the geometric requirements for openings may vary according to building function and spatial configuration; therefore, they cannot be applied as a single universal standard for all classrooms.

Referring to the Green Building Council Indonesia (GBCI) benchmark for daylighting assessment, this study also evaluated the coverage of natural lighting using the P300 indicator. This indicator represents the estimated percentage of the measurement-plane area receiving an illuminance level of ≥ 300 lux, based on 25 equally sized grid cells in each classroom. The measurement results show that the highest average P300 value was recorded in Lower B, at 29.71%, followed by Middle A (18.86%), Middle B (9.71%), Upper A (5.71%), Upper B (0.57%), and Lower A (0%). Although the average P300 value for Lower B approached the 30% benchmark, this coverage level was achieved in only three of the seven measurement sessions, namely at 9:00 a.m., 1:00 p.m., and 2:00 p.m., with a coverage value of 36% in each session. Meanwhile, the other five classrooms failed to achieve 30% coverage in all measurement sessions. These findings indicate that most of the measurement-plane area did not receive natural illuminance of ≥ 300 lux during the observation period, even when the average room illuminance was relatively high. Accordingly, a high illuminance level does not necessarily ensure that a large proportion of the room receives natural light at a specified threshold.

These comparisons become particularly interesting when considered in relation to actual illuminance performance. Lower A had the highest WWR and WFR values, at 15.06% and 26.55%, respectively, but produced an Eavg of only 58.40 lux. Meanwhile, Lower B and Middle A had almost identical opening proportions, with WWR values of 14.41% and 14.47% and WFR values of 24.89% and 25.02%, respectively, yet their Eavg values differed by approximately 2.17 times. This finding indicates that opening proportions that nominally exceed residential reference thresholds do not necessarily provide adequate illuminance for educational functions. Consistent with Baker and Steemers (2002), daylight reception and distribution should be understood through the interaction of room geometry, opening configuration, access to daylight, shading elements, and surrounding environmental conditions. Therefore, evaluating daylighting performance requires more than examining average illuminance levels; it must also consider area coverage, uniformity, spatial and temporal distribution, and the architectural characteristics of the space. This approach provides a more comprehensive understanding of existing daylighting performance in historic buildings that have been adaptively reused as educational facilities, without assuming causal relationships between architectural factors that have not yet been tested.

CONCLUSION

The findings indicate that daylighting performance in the six classrooms of SD Tumbuh 3, located within the Dalem Mangkubumen complex, has not been sufficient to independently and consistently meet the classroom illuminance requirement of 350 lux. Temporally, 6 of the 42 observations met the reference level, while the remaining 36 did not. In terms of spatial distribution, only 9.33% of the 1,050 point-time readings achieved an illuminance level of ≥ 350 lux. An evaluation against the GBCI benchmark also indicates that the minimum coverage requirement of 30% of the area receiving natural illuminance of ≥ 300 lux was achieved in only three of the 42 classroom-session observations, all of which occurred in Lower B. Furthermore, the uniformity index (U_o) generally indicates an uneven lighting distribution, demonstrating that average illuminance levels do not fully represent the lighting conditions across individual working planes. In addition, the findings reveal that high average illuminance is not necessarily accompanied by adequate uniformity and lighting coverage, as demonstrated by Lower B and Middle A. Conversely, Lower A exhibited a relatively uniform distribution but maintained a low illuminance level. These findings emphasize the importance of evaluating daylighting performance through an integrated assessment of illuminance levels, area coverage, uniformity, and spatial and temporal distribution. In terms of geometric characteristics, the data indicate that opening proportions alone do not guarantee adequate illuminance for educational functions. Lower A had the highest WWR and WFR values but produced a low Eavg, whereas Lower B and Middle A, despite having almost identical opening proportions, exhibited an approximately 2.17-fold difference in Eavg. Consistent with Baker and Steemers (2002), these findings highlight the importance of considering opening configurations, room geometry, shading elements, and environmental conditions when interpreting variations in daylighting performance. Thus, a multidimensional evaluation of daylighting performance provides an important basis for assessing the suitability of existing lighting conditions for the new functional requirements of historic buildings.

The evaluation findings also have implications for lighting management in inclusive educational spaces that accommodate the diverse visual needs and sensory sensitivities of their users, including children with special needs. The identified limitations in illuminance levels and uneven light distribution may affect object visibility and visual comfort during learning activities. Therefore, identifying areas with low or uneven illuminance can provide a basis for considering lighting strategies that address illuminance adequacy, distribution uniformity, and flexible lighting control according to activity requirements and user needs. One potential alternative for further investigation is the implementation of smart lighting through the integration of natural and artificial lighting, using dimmable lamps, illuminance sensors, and lighting controls based on activity zones. Given that the study object is a cultural heritage building, such strategies should prioritize minimal intervention and removable installations that do not damage historic architectural elements, in accordance with the conservation principles established in the Burra Charter (Australia ICOMOS 2013). Implementing an adaptive lighting system is expected to support the visual requirements of educational activities while preserving the building's architectural character and historical significance, although its effectiveness requires further investigation.

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LIMITATIONS AND RECOMMENDATIONS

This study has several limitations, particularly the measurement period, which was insufficient to represent variations in natural lighting throughout the year. In addition, the research adopted a descriptive-evaluative approach and did not isolate the effects of individual architectural variables on daylighting performance. As explained by Baker and Steemers (2002), the reception and distribution of natural light are influenced by the interaction of opening configurations, room geometry, shading elements, environmental obstructions, and the characteristics of reflective surfaces. Consequently, the relationships between these factors and the measurement results obtained in this study cannot yet be established as causal.

Future research is recommended to employ daylighting simulations validated against field measurements to identify the individual effects of and relationships between architectural variables. The comparison between Lower B and Middle A presents an interesting case for further investigation because the two classrooms have almost identical opening configurations and proportions but produce different illuminance levels. Furthermore, an evaluation of the integration of natural and artificial lighting (mixed lighting), including the potential use of lighting control systems based on activity zones and user requirements, could be conducted to assess improvements in illuminance adequacy and uniformity. Such research could also be extended to evaluate visual comfort and the individual needs of users in inclusive educational environments. In this way, the development of lighting strategies can be grounded in empirical evidence while taking into account the limitations on interventions in cultural heritage buildings.

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