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Multi-Objective Optimisation of Skylight Design Parameters for a Low-rise Building in the Tropics

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Abstract. Skylight is an effective strategy for maximising daylight penetration while minimising electrical lighting energy demand in buildings. However, in tropical climate regions, skylight can be problematic due to the risk of excessive sunlight. This study aimed to optimise skylight design parameters using multi-objective optimisation (MOO) approach through a case study of a low-rise building with office rooms configured to surround a skylight in the tropical climate of Yogyakarta, Indonesia. It was conducted using computational modelling and simulation with *RadianceIES* tools in *IES-VE 2019* software. The parameters examined included skylight shape, opening area, and thickness, while the performance indicators were spatial daylight autonomy ($sDA_{300/50\%}$), average daylight factor (DF_{ave}), and annual sunlight exposure ($ASE_{1000,250}$). The sensitivity analysis showed that skylight opening area significantly influenced daylight performance. Moreover, the optimum design, drawn from the objective function *f* and Pareto frontiers, was a rounded trapezium skylight with an opening area of 897 m^2, achieving $sDA_{300/50\%}$–$ASE_{1000,250}$ = 35%, DF_{ave} = 0.9%, and mean distance to the utopia point of 64.1%. These results could serve as a guide for architects and engineers in designing skylight for typical buildings.

Keywords: Daylight; Low-rise building; Multi-objective optimisation; Simulation; Skylight

1. Introduction

Issues on energy consumption and climate change are dominant discourses in all aspects of life. The United Nations reported that 36% of global energy consumption is allocated for buildings and construction (IEA, 2023a; 2023b; UNEP, 2022), facilitating the drive for green and sustainable building campaigns (Doan *et al.,* 2021; Fatriansyah, Abdillah, and Alfarizi, 2021). Energy consumption by buildings accounts for approximately 25% of operational costs, with around 20%–45% attributed solely to electric lighting (Tiwari, Tiwari, and Shyam, 2016). This high demand for electric lighting energy has led to a more efficient way of dealing with lighting systems in buildings, particularly with the accommodation of daylighting strategies, such as skylight (Marzouk *et al.,* 2022; Hakim *et al.,* 2021).

Skylight is among the most popular daylighting strategies for maximising daylight penetration and uniformity while minimising artificial lighting demand (Marzouk, ElSharkawy, and Eissa, 2020; Li *et al.,* 2019). It is specifically suitable for low-rise buildings with large floor areas (ASHRAE, 2019). Introducing daylight through skylight also improves

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occupants' comfort, performance, health, and well-being (Lie *et al.,* 2022; Pastilha and Hurlbert, 2022; Hartstein, Tuzikas, and Karlicek, 2020; Van Creveld and Mansfield, 2020).

The application of skylight can be problematic in tropical climate regions due to the risk of excessive sunlight. Therefore, studies are required to investigate skylight application in such conditions, specifically in Indonesia. Among various methods, modelling and simulation-based approaches are widely used to provide an efficient, simple, and reliable means of studying daylight performance in buildings with skylight (El-Abd *et al.,* 2018).

1.1. Skylight performance optimisation

Skylight is a daylight opening or aperture installed on a building roof, with its relative size often expressed as the ratio between the skylight size and the total floor area (SFR). Typically, various skylight types have different performance characteristics (Fakhr *et al.,* 2023; Shirzadnia, Goharian, and Mahdavinejad, 2023; Mangkuto *et al.,* 2022). A clerestory skylight can be adapted to the room wall, facilitating deeper penetration of daylight. A sawtooth skylight can be adjusted toward the path of the sunlight, displaying a responsive pattern to the sun trajectory. A monitor skylight shows a more consistent performance than other types throughout the year. However, a flat skylight can provide high, low-glare illumination and is suitable for large areas in any climate (Mavridou and Doulos, 2019).

Several studies have been conducted on building daylight performance with skylight applications, although most were carried out in sub-tropical or temperate climate conditions (El-Abd *et al.,* 2018; Motamedi and Liedl, 2017). In these regions, the apparent position of the sun (solar radiation) consistently changes due to geographical location. In tropical regions, there is a relatively high amount of annual solar radiation, consistently available throughout the year due to proximity to the equator (Mangkuto, Rohmah, and Asri, 2016). Therefore, top lighting strategies, including skylight, can be problematic for low-rise buildings, due to the risk of excessive direct sunlight and heat accumulation.

Among others, parametric modelling and optimisation studies for skylight have been carried out by Li *et al.* (2023), Marzouk, ElSharkawy, and Eissa (2020), and Motamedi and Liedl (2017) in the northern hemisphere. However, various optimisation methods are constrained by the specific case, variables, and parameters, which may not apply to other climate conditions, building types, and floor areas. Interestingly, no specific studies have discussed the method of skylight design optimisation that simultaneously consider its shape, size, and thickness, particularly for low-rise buildings in tropical climate regions, where annual daylight penetration is relatively high.

1.2. Aims and objectives

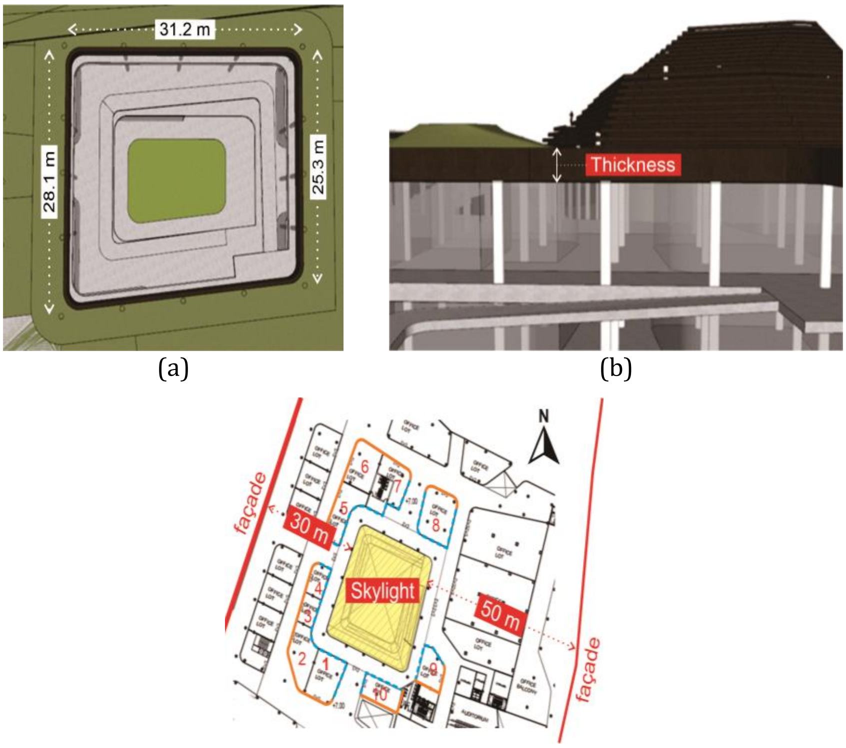
This study aimed to investigate optimisation methods of skylight in a low-rise building, namely the Super Creative Hub Universitas Gadjah Mada (SCH UGM) in Yogyakarta, Indonesia. Building daylighting performance, specifically skylight shape, area, and thickness, was evaluated. The objectives were to examine the most influential parameters in optimising skylight design solutions that fulfil the performance criteria using computational modelling and simulation, with a case study in Yogyakarta, Indonesia, representing a tropical climate region (Faridah *et al.,* 2024; Mangkuto *et al.,* 2018). The performance criteria adopted daylight metrics incorporated in LEED v4.1 by USGBC (2019).

2. Methods

2.1. Case study

The building examined in this study was located in Yogyakarta, Indonesia (7°8' S, 110°4' E), an area characterised by a hot, humid climate, and sunshine throughout the year. The intensity of solar irradiance can be excessive, reaching as high as 2.49 kW/m^2 (Tutuko, 2015), which is higher than the world average of 1.37 kW/m² (Karki, 2017). The building comprised two storeys with a skylight to illuminate the rooms. The skylight examined had an opening area of 828 m², a trapezium shape, and rounded corners, as shown in Figure 1a, b, and c. The opening was not covered by glazing materials to allow natural ventilation.

A total of ten office rooms were located on the second floor, each facing the central point below the skylight and constructed from clear glass, indicated by the dashed blue line. Meanwhile, the tangerine color represents the façade of each observed room. The rooms had a total floor area of 966 m², and the distance between the skylight and the building façade ranged from 30 to 50 m. The intention was to rely on daylight as the only light source during the day. Considering the skylight opening area and the total floor area, the skylight-to-floor ratio (SFR) value was 85.8% in the baseline design scenario.



(a) (b)

(c)

Figure 1 Perspective view for (a) top view, (b) side view, and (c) the surrounding office rooms

2.2. Modelling and simulation

Building material properties, workplane height, and sky conditions were defined in *IES-VE*, according to the Indonesian National Standard (SNI) (BSN, 2020), and with the input of the Perez All-Weather sky. The room surface reflectances and glazing transmittance of the building model are summarised in Table 1. Three skylight shapes were considered, namely rounded trapezium, rectangle, and rounded rectangle, as shown in Figure 2.

Table 1 Surface reflectances and glazing transmittance of the building model

Variable	Value
Ceiling reflectance (%)	90
Floor reflectance (%)	25
Façade glazing transmission (%)	90

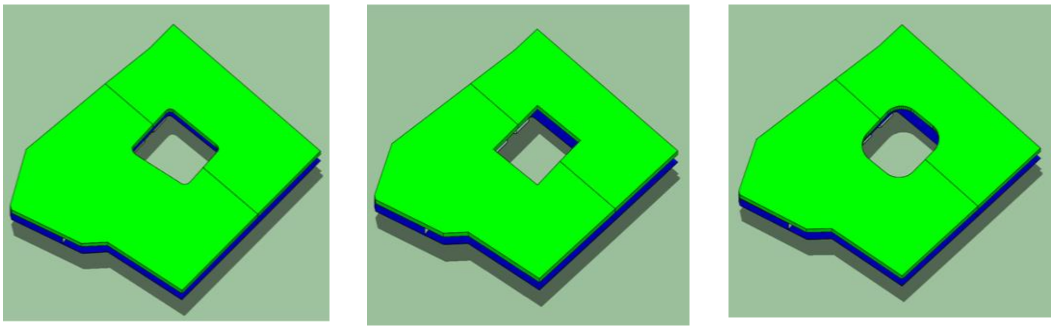


Figure 2 Skylight model shapes of (a) rounded trapezium, (b) rectangle, and (c) rounded rectangle

Annual daylighting simulation was conducted at 08.00–16.00 hrs daily with no electric lighting installed. The model used *Meteoronorm* 2006 weather data, and the varied parameters included the skylight shape, size, and thickness. The size was adjusted by widening and straightening each side of the skylight by 1 m, therefore altering the opening area. The skylight was straightened until its performance met the minimum value and widened until each side touched the outer sides of the office rooms.

The skylight thickness corresponded with the rooftop structure, serving as a green roof. The rooftop combined 1 m depth and 0.2 m planting media for plants. Consequently, the thickness varied from 1.2 m up to 2.2 m, with the maximum value being where the loads can withstand the roof structure (Cascone, 2019), as summarised in Table 2.

Table 2 Summary of input parameter variations

Parameter	Baseline	Variation range	Interval
Shape	Rounded trapezium	Rectangle; rounded rectangle	-
Size	31.2 m × 28.1 m	Increasing each side by 1 m	1 m
Thickness	1.7 m	1.2 ~ 2.2 m	0.25 m

2.3. Assessment

The daylighting performance was evaluated based on the following metrics:

1. Average Daylight Factor (DF_{ave}) represents the average DF for each grid on the floor area. LEED requires a minimum DF of 2% (USGBC, 2019).
2. Spatial Daylight Autonomy 300 lx/50% ($sDA_{300/50\%}$) denotes the percentage of floor area receiving daylight illuminance of more than 300 lx in at least 50% of the annual working hours. LEED (2019) demands a minimum $sDA_{300/50\%}$ of 55%.
3. Annual Sunlight Exposure 1000 lx, 250 hours ($ASE_{1000,250}$) denotes the percentage of floor area receiving direct sunlight of more than 1000 lx in at least 250 hours of the annual working hours. LEED (2019) recommends $ASE_{1000,250}$ of no more than 10%.

Sensitivity analysis was performed to investigate the significant correlation between the design parameters (input) and the performance indicators (output) (Iooss and Saltelli, 2017). For each skylight shape, sensitivity analysis was conducted using multilinear regression to obtain the standardised regression coefficients using equation (1).

$$y'_i = \beta_1' x'_{1,i} + \beta_2' x'_{2,i} + \varepsilon_i, \qquad i = 1, 2, \ldots, n \tag{1}$$

where β_1', β_2' were the standardised regression coefficients (SRC), y'_i was the standardised output variable, $x'_{1,i}$ and $x_{2,i}$ were the standardised skylight opening area and thickness, and ε_i was the residual error. The y' variable was evaluated for the three daylight metrics, namely DF_{ave}, $sDA_{300/50\%}$, and $ASE_{1000,250}$. The standardisations were performed using equation (2).

$$y'_i = \frac{y_i - \bar{y}}{\sigma_y};\ x'_{ni} = \frac{x_{ni} - \overline{x_n}}{\sigma_{x_n}} \quad (2)$$

where y_i and x_{ni} were the actual output and input variables, $\bar{y}$ and $\overline{x_n}$ were the means of the input and output variables, while σ_y and σ_{x_n} were the standard deviations of the input and output variables. SRC values of 1 or −1 indicate a highly significant (positive or negative) influence on the output as a function of the input (Atthaillah *et al.*, 2022a; 2022b; Mangkuto, Rohmah, and Asri, 2016).

Two approaches were proposed in this study to find the optimum solutions. In the first approach, the optimum design parameters were obtained by evaluating objective function *f*, defined as the difference between $sDA_{300/50\%}$ and $ASE_{1000,250}$, see equation (3).

$$f = \mathrm{sDA}_{300/50\%} - \mathrm{ASE}_{1000,250} \quad (3)$$

The results were subsequently ranked based on the resulting *f* values. A combination of design parameters that yielded the highest *f* value was considered the optimum solution. In the second approach, a graphical optimisation method with Pareto frontiers was applied, together with several additional rules. The simulation results of all considered combinations were grouped and paired based on the conflicting indicators for every two different indicators, which required a trade-off. Three pairs of metrics were selected: $sDA_{300/50\%}$ vs $ASE_{1000,250}$; $sDA_{300/50\%}$ vs DF_{ave}; and DF_{ave} vs $ASE_{1000,250}$. The pairs were subsequently sorted to rank the optimum solutions based on the following algorithms:

1. All non-dominated solutions (Pareto solutions) were sorted based on constraints as defined by equation (4), (5), and (6).

$$\mathrm{DF}_{\mathrm{ave}} \geq 2\% \quad (4)$$

$$\mathrm{sDA}_{300/50\%} \geq 50\% \quad (5)$$

$$\mathrm{ASE}_{1000,250} \leq 10\% \quad (6)$$

2. The sorted Pareto solutions were filtered and accepted as the 'optimum' solution when the requirements in two pairs of metrics were satisfied.
3. The filtered solutions were ranked based on (1) the mean distance of the solutions to the utopia point; and (2) the number of Pareto frontiers. The optimum solution belonged to Pareto frontiers in both pairs of metrics and had the nearest distance to the utopia point. In this case, the utopia point was defined as $f_i^0 = \{f_i(x))\ |x \in S\}, i = 1, 2, 3, \dots, k$, where k was the number of the objective functions to be minimised.

The distance to the utopia point was subsequently calculated and compared (see Figure 3). In the $sDA_{300/50\%}$ vs $ASE_{1000,250}$ pair, the $sDA_{300/50\%}$ should be maximised, while $ASE_{1000,250}$ should be minimised. Therefore, the utopia point lay on the lower right corner of the Cartesian diagram as a 100% value. The distance of each Pareto solution to the utopia point was obtained using equation (7).

$$d(\mathrm{sDA}_{300/50\%}\ \mathrm{vs}\ \mathrm{ASE}_{1000,250}) = \sqrt{(100 - \mathrm{sDA}_{300/50\%})^2 + (\mathrm{ASE}_{1000,250})^2} \quad (7)$$

A similar expression could be applied for the pair of DF_{ave} vs $ASE_{1000,250}$. Meanwhile, both metrics should be maximised in the $sDA_{300/50\%}$ vs DF_{ave} pair. Therefore, the utopia point lay on the upper right corner of the Cartesian diagram and had a 100% value for each. The distance to the utopia point could then be expressed in equation (8).

$$d(\mathrm{sDA}_{300/50\%}\ \mathrm{vs}\ \mathrm{DF}_{\mathrm{ave}}) = \sqrt{(100 - \mathrm{sDA}_{300/50\%})^2 + (100 - \mathrm{DF}_{\mathrm{ave}})^2} \quad (8)$$

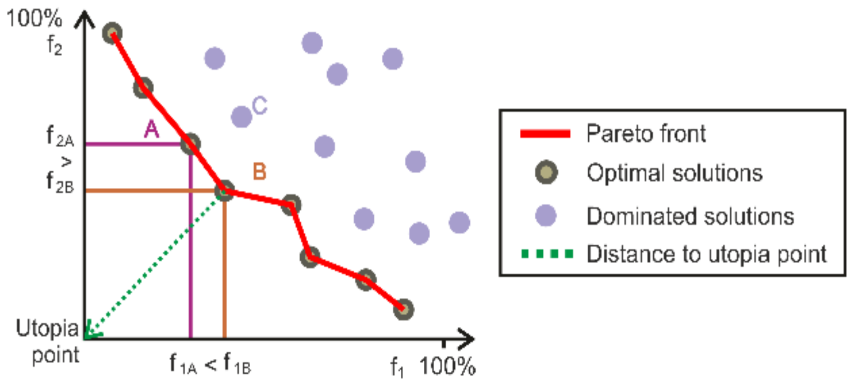


Figure 3 Visualisation of Pareto Frontiers for two-objective spaces

3. Results and Discussion

A total of 85 simulations were conducted to examine the daylighting performance of the office rooms. The simulation results for the baseline scenario are shown in Table 3. The baseline scenario did not meet the LEED v4.1 standard, achieving a $sDA_{300/50\%}$ of only 31.9%, although the standard for $ASE_{1000,250}$ of less than 10% was met. Optimising the design parameters, as described in the following subsections, is necessary.

Table 3 Results of the baseline design simulation

Shape	Area (m^2)	Thickness (m)	$sDA_{300/50\%}$ (%)	$ASE_{1000,250}$ (%)	DF_{ave} (%)
Trapezium	828	1.7	31.9	0.6	0.7

3.1. Sensitivity analysis

The SRC and R^2 of the multilinear model are shown in Table 4. The scatter plots of all metrics with respect to the skylight shape, area, and thickness are shown in Graphical plots for all parameters and indicators were linearly correlated, as indicated by the high R^2 values.

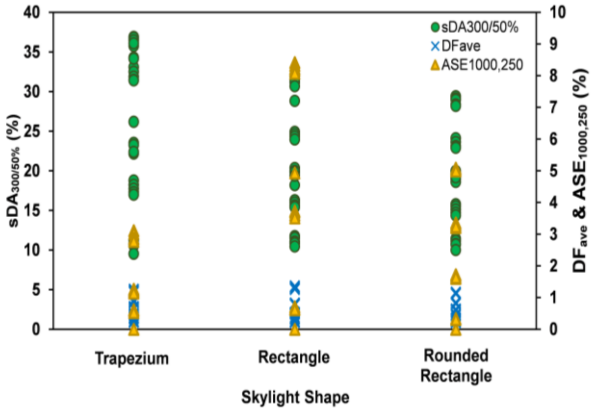
Table 4 SRC and R^2 of all parameters based on the multilinear regression

Shape	Parameter	Standard Regression Coefficient			R^2		
		$sDA_{300/50\%}$	DF_{ave}	$ASE_{1000,250}$	$sDA_{300/50\%}$	DF_{ave}	$ASE_{1000,250}$
Trapezium	Area	0.97	0.97	0.86	0.93	0.95	0.72
	Thickness	−0.05	−0.07	−0.03			
Rectangle	Area	0.98	0.97	0.88	0.98	0.94	0.78
	Thickness	−0.12	−0.09	−0.15			
Rounded Rectangle	Area	0.97	0.97	0.94	0.95	0.94	0.87
	Thickness	−0.09	−0.06	−0.01			

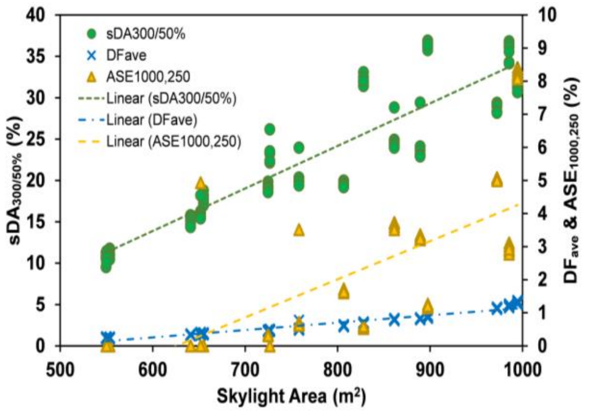
The skylight opening area significantly influenced all daylight metrics, as indicated by the SRC values greater than 0.8. The positive SRC values indicate positive correlations between the skylight area for all indicators. For the trapezium shape, every 10 m^2 increase in the skylight area corresponded to a rise of 0.64%, 0.02%, and 0.06% of $sDA_{300/50\%}$, DF_{ave}, and $ASE_{1000,250}$, respectively. A similar 10 m^2 area increase for the rectangular shape resulted in 0.46%, 0.02%, and 0.18% changes in the respective metrics. Likewise, for the rounded rectangular skylight, the equivalent area increase corresponded to a rise of 0.4%, 0.02%, and 0.12% in $sDA_{300/50\%}$, DF_{ave}, and $ASE_{1000,250}$, respectively. The trapezium shape showed the highest improvement in $sDA_{300/50\%}$ while having the lowest increase in

$ASE_{1000,250}$, demonstrating the effectiveness of the changes. The increase in average daylight factor was similar regardless of the skylight shape.

The skylight thickness did not significantly impact the daylight metrics, as indicated by the low SRC value. The correlations between each shape and indicator were highly linear, as demonstrated by the high values of R^2, indicating the linearity and the percentage of variation that could be explained by the model. The correlations were more than 0.93 for $sDA_{300/50\%}$ and DF_{ave}, but were only 0.72 for $ASE_{1000,250}$, although it was still considered linear.



(a)



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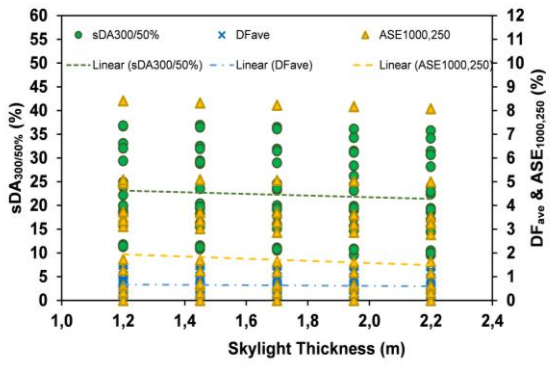


(c)

Figure 4 Scatter plot of all metrics of the skylight (a) shape, (b) opening area, and (c) thickness

The best skylight shape was the rounded trapezium, as at the baseline size (828 m^2), it yielded the highest $sDA_{300/50\%}$ (31.9%), while the other shapes required more than 990 m^2

area to meet this value. The worst shape was the rounded rectangle, which required the largest skylight area to meet the value of the baseline size from the rounded trapezium. The correlation between the skylight area and the mean values of the three daylight metrics is shown in Figure 5.

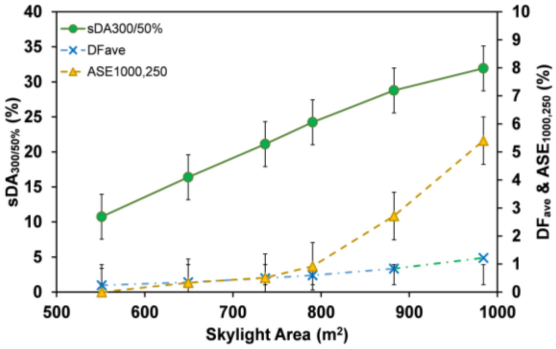


Figure 5 Mean values of the daylight metrics with respect to the skylight opening area; error bars represent standard deviation

The skylight opening area was directly proportional to the daylight metrics values. However, the DF_{ave} gradient was less steep than for $sDA_{300/50\%}$ and $ASE_{1000,250}$, as DF_{ave} only considered the diffuse daylight illuminance. The trapezium-shaped skylight with an 897 m^2 opening area performed the best since it was the smallest area that yielded $sDA_{300/50\%}$ of around 30%, with $ASE_{1000,250}$ as low as 1%. Expanding the opening area beyond this value would no longer raise the overall daylight performance, as $ASE_{1000,250}$ would become too high, significantly increasing the risk of visual discomfort.

The multilinear regression suggested that skylight thickness did not significantly affect the daylight metrics, with SRC values no more than 0.15 due to the excessive amount of solar radiation in the location. Therefore, the thickness might not be sufficient to control daylight availability in the office rooms. The relatively large skylight opening area effectively reduced the ratio between the skylight thickness and its area, allowing solar radiation to penetrate regardless of its thickness.

3.2. Optimisation

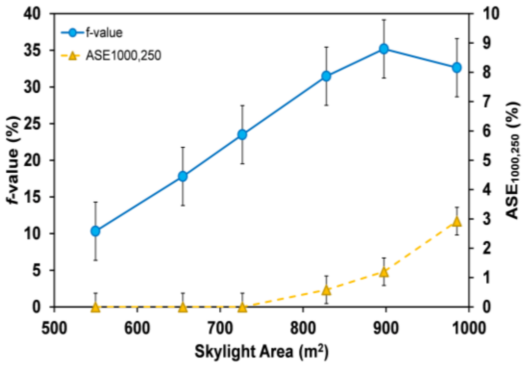
Table 5 shows the five input combinations yielding the greatest objective values, *f*. Based on the objective, no solution achieved the LEED v4.1 standards for $sDA_{300/50\%}$, but all solutions met the standard for $ASE_{1000,250}$. The optimum solution was the trapezium skylight with an area of 897 m^2, yielding f = 35.2%. In the second place, the trapezium skylight had an area of 985 m^2 and f = 32.6%. Since the optimisation comprised both $sDA_{300/50\%}$ and $ASE_{1000,250}$, it tended to choose the optimum solution with higher $sDA_{300/50\%}$ and lower $ASE_{1000,250}$.

Table 5 Five combinations with the greatest objective (*f*) values

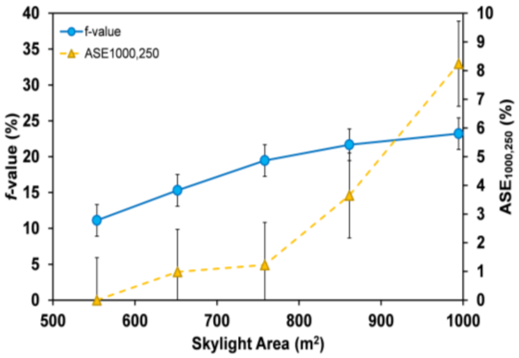
Shape	Area (m^2)	$sDA_{300/50\%}$ (%)	DF_{ave} (%)	$ASE_{1000,250}$ (%)	*f* (%)
Trapezium	897	36.4	0.9	1.2	35.2
Trapezium	985	35.6	1.2	2.9	32.6
Trapezium	828	31.9	0.7	0.6	31.3
Rounded rectangle	972	28.8	1.1	5.0	23.7
Trapezium	727	23.5	0.5	0.0	23.5

The simulation results showed that increasing the opening area of the trapezium-shaped skylight would eventually increase all metrics values. However, the opening area had a particular optimum value that was achieved at 897 m^2. Regarding the *f* values, every

10 m^2 increase in the skylight area corresponded to an increase of 0.57%, 0.28%, and 0.28% of the *f* value for the trapezium, rectangle, and rounded rectangle shapes, respectively. The trends of the *f* value with respect to the skylight opening area for each shape are shown in Figure 6.



(a)



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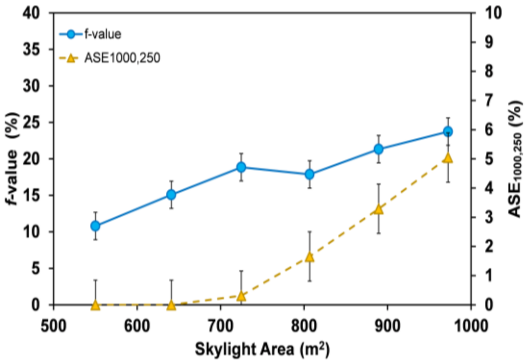
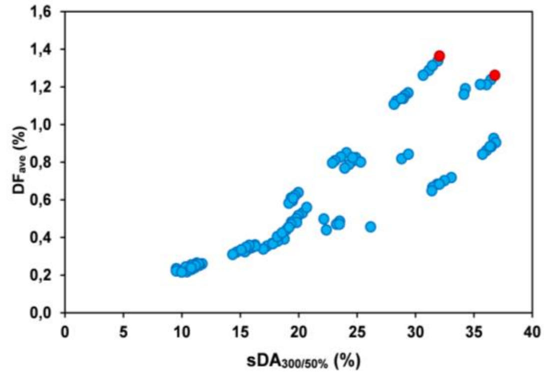


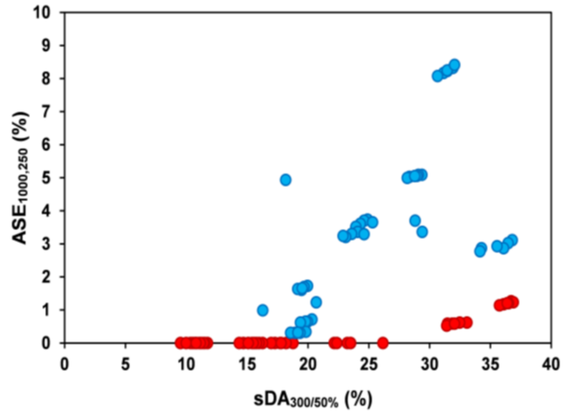
(c)

Figure 6 Objective function *f* with respect to the trapezium skylight opening area for (a) trapezium; (b) rectangle; and (c) rounded rectangle; error bars represent standard deviation

The scatter plots of the three daylight metrics pairs ($sDA_{300/50\%}$ vs DF_{ave}; $sDA_{300/50\%}$ vs $ASE_{1000,250}$; and DF_{ave} vs $ASE_{1000,250}$) are respectively shown in Figure 7. Red dots in the scatter plots represent the solutions of the Pareto frontiers. Figure 7(a) shows that there were only two optimum solutions based on the $sDA_{300/50\%}$ vs DFave relation, while more optimum solutions were found in Figure 7(b) and Figure 7(c), including conflicting indicators. Five combinations of Pareto frontiers with the smallest dave are shown in Table 6.



(a)



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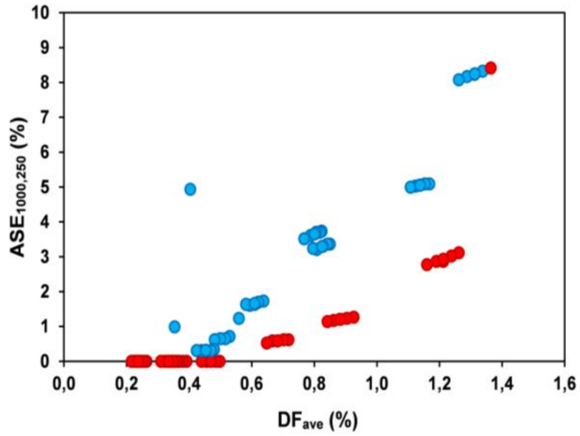

(c)

Figure 7 Scatter plot for (a) $sDA_{300/50\%}$ vs DF_{ave}, (b) $sDA_{300/50\%}$ vs $ASE_{1000,250}$, and (c) DF_{ave} vs $ASE_{1000,250}$

Table 6 Five combinations that belonged to the Pareto frontiers and yielded the smallest d_{ave}

Shape	Area (m^2)	$sDA_{300/50\%}$ (%)	DF_{ave} (%)	$ASE_{1000,250}$ (%)	d_{ave} (%)
Trapezium	897	36.4	0.9	1.2	64.1
Trapezium	985	35.6	1.2	2.9	64.5
Trapezium	828	31.9	0.7	0.6	66.7
Rectangle	995	31.5	1.3	8.2	66.9
Rounded rectangle	972	28.8	1.1	5.0	68.3

The most optimum solution was the trapezium skylight with an 897 m^2 opening area, yielding a d_{ave} of 60.5%. In the second place, there was a trapezium skylight with a 985 m^2

area and a d_{ave} of 60.8%. These two solutions matched the optimum solutions obtained using the objective function f. Optimisations based on f value and d_{ave} resulted in the same order of optimum solution for the first three solutions, as shown in Table 7. However, the order started to change from the fourth solution onward.

The area parameter significantly and positively affected all indicators, as all of the SRC values were near to one, which was consistent with other studies (Marzouk, ElSharkawy, and Eissa, 2020; Fang and Cho, 2019), demonstrating the significant effects of skylight area on daylighting performance. This pattern has been widely acknowledged worldwide when designing skylight.

Despite the negative correlation, the impact of the variation in skylight thickness was less significant. The results contradicted Irakoze, Lee, and Kim (2020), showing the significant effects of skylight thickness on daylighting performance. However, this study was carried out in a space with a relatively small skylight compared to the current study. Further investigation was required to examine the range of skylight areas in which the thickness significantly affected daylighting performance.

Table 7 Five combinations that shared the same optimum solutions

Design parameter		Simulation results			Rank based on	
Shape	Area (m^2)	sDA$_{300/50\%}$ (%)	DF$_{ave}$ (%)	ASE$_{1000,250}$ (%)	f	d_{ave}
Trapezium	897	36.4	0.9	1.2	1	1
Trapezium	985	35.6	1.2	2.9	2	2
Trapezium	828	31.9	0.7	0.6	3	3
Rounded rectangle	972	28.8	1.1	5.0	4	5
Trapezium	727	23.5	0.5	0.0	5	8

Current standards and guidelines in Indonesia have not incorporated dynamic daylight metrics such as sDA and ASE. Therefore, the current study utilized LEED v4.1 by USGBC as benchmarking. LEED was developed mainly in the United States, which has a different climate from Indonesia. Considering the subjective nature of daylighting along with regions, climates, and cultures, there was a crucial need to develop guidelines incorporating dynamic daylight metrics for Indonesia.

4. Conclusions

In conclusion, design optimisation of skylight shape, area, and thickness was conducted in this study for a low-rise building in Yogyakarta, Indonesia, with respect to daylighting performance. The skylight opening area significantly influenced the daylight metrics, with all three SRC values higher than 0.85. The most optimum design was the rounded trapezium skylight with an opening area of 897 m^2, achieving sDA300/50% – ASE$_{1000,250}$ = 35%, D$_{Fave}$ = 0.9%, and a mean distance to the utopia point of 64.1%. The results were expected to benefit architects and engineers in designing skylight for low-rise buildings in the tropics, although only the daylighting performance of skylight was evaluated. In real-world practices, incorporating skylights influenced other indoor environmental quality (IEQ) parameters, such as thermal, air quality, and acoustics. Therefore, future studies were recommended to investigate daylighting performance along with these parameters to understand the phenomena holistically.

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