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Daylighting Evaluation of Perforated Screen Façade with Light Shelf in the Tropics

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Abstract

The use of large glass facades in buildings without external shading devices leads to a high daylight level, uneven daylight distribution, and glare. A perforated screen facade (PSF) is one of the shading systems that can provide daylight and view and prevent direct solar radiation into a building. More research is needed about the daylight performance of PSF in integration with daylighting systems in the tropics. A combination of PSF and light shelf (LS), a daylighting system that can redirect daylight to the ceiling and enhance daylight distribution, is proposed to improve daylight levels and reduce glare. The research aims to evaluate the daylight performance of PSF and LS in the tropics. The research method is experimental with simulation utilizing IES-VE Radiance IES. Average Daylight Factor (DFavg), Useful Daylight Illuminance (UDI), and Daylight Glare Probability (DGP) of a room with a side window were compared with a room with PSF and LS. The results showed that implementing PSF and LS improved daylight performance by lowering the DFavg by 55%, increasing the UDI, and reducing the DGP.

INTRODUCTION

There is a high potential for using daylight in tropical buildings. Daylight in this area is abundant due to the intense sun intensity and more extended illumination period during the daytime (Roshan and Barau, 2016). Research on daylighting in tropical regions shall take into account inconsistent cloud formation of intermediate skies (Lim and Heng, 2016). According to Zain-Ahmed et al. (2002), the global illuminance at noontime reaches 80 Klux and 60 Klux in March and December, respectively.

Many high-rise office buildings in the Tropics have a large, glazed façade, resulting in uneven daylight distribution and potential glare risk without appropriate shading devices (Lim and Heng, 2016; Lavin and Fiorito, 2017). Glare problems lead building users to block the glazed facade with internal shading, such as curtains or internal blinds, and use electric lighting instead (Lim and Heng, 2016). Thus, shading is required in the Tropics to prevent direct sunlight while allowing daylight to enter through a side window (Chaiwiwatworakul and Chirarattananon, 2013). Proper shading devices, particularly exterior shading devices, can effectively control solar radiation (Al-Tamimi and Fadzil, 2011; Gupta and Deb, 2023) and improve daylight performance (Luca et al., 2022).

Perforated Screen Façade as A Shading System

Perforated screen facades (PSF) are opaque lattices with holes that can be different in number, size, shape, and arrangement of holes. PSF is like mashrabiya, a wooden lattice screen (Kamal, 2014) of cylinders that functions as a shading device to protect openings of Middle Eastern buildings (Sherif et al., 2012a). PSF is used in front of the glazed façade to control solar radiation entering a building while providing daylight (Chi Pool, 2019) and view (Srisamranrungruang and Hiyama, 2020). The perforated screen's opaque parts reflect sunlight and function as a shading system (Chi et al., 2016).

As shown in Table 1, previous research has studied various design variables for PSS, including perforation percentages (Sherif et at., 2012a), opening aspect ratio of the screen, and solar screen rotation angle (Sherif et al., 2012b), opening aspect ratio and solar screen axial rotation (Sabry et al., 2014), and perforated screen's thickness, matrix, and separation distance (Chi Pool, 2019). The research contexts of previous research were desert (Sherif et al., 2012a; Sherif et al., 2012b; Sabry et al., 2014), Mediterranean climate (Chi Pool, 2019), warm and temperate climate (Srisamranrungruang and Hiyama, 2020). Most of the research took context in the non-tropic areas and showed the capability of PSF in reducing glare, improving daylight distribution, and reducing energy demand. Research about PSF's daylight performance in the Tropics with intermediate sky conditions is still limited.

Light Shelf as A Daylighting System

A light shelf (LS) is a horizontal or inclined plane positioned above the eye level and in the upper half of the window, internally or externally (Kontadakis et al., 2018) or in combination. LS can control and redistribute daylight through reflection on its upper surface. LS improves daylight admission, gives shading near the side window (Kontadakis et al., 2018), and reduces glare (Moazzeni and Ghiabaklou, 2016) by reflecting daylight into the ceiling and the room.

LS can be static or sun-tracking, flat or curved, and using specular reflective material on its uppersurface. In a sun-tracking LS, the angle is mainly variable to respond to the sun solar altitude. The high specular reflectivity materials of LS including mirror glass, aluminium (Warrier and Raphael, 2017), reflective glass, stainless steel, or highly reflective aluminium tapes (Hashemi, 2014).

Previous research on the daylight performance of external LS was done by Berardi and Anaraki, 2015. The research showed that LS improves the Useful Daylight Illuminance level primarily at 6 m in front of the side window and the daylight distribution in a south-facing office building. Warrier and Raphael, 2017 evaluated the LS potential in improving daylighting performance and visual comfort. The study showed that the adequately designed external LS can shade the lower window and perform better than a conventional shading system. The energy consumption for air conditioning and lighting of LS was studied by Lee et al., 2018 and showed that the optimum LS was 0.6 wide with an angle of 30° for efficient energy saving. Previous research also studied the combination of LS with other daylighting systems, such as horizontal light pipes and blinds (Elsiana et al., 2021), prism sheets 1.8 m above the floor (Lee and Seo, 2020), and LS with shading system including external blinds in south facing classroom (Meresi, 2016).

Table 1. Studies on Perforated Screen as A Shading System

Authors	PSF Design variables	Contexts	Performances	Combination Perforated Screen with Daylighting Systems
Sherif et al., (2012a)	Perforation percentage of screen	Desert	Daylighting	Side window, light transmittance 85%
Sherif et al., (2012b)	Solar screen rotation angle and its opening aspect ratios	Desert	Daylighting	Side window
Sabry et al., (2014)	Solar screen axial rotation and opening aspect ratio	Desert	Daylight, energy	Side window, light transmittance 88%
Srisamranrungruang and Hiyama (2020)	Perforated percentage	Warm and temperate of Japan	Natural ventilation, daylighting, thermal	Side window, light transmittance 86%
2019)	Matrix, thickness, and separation distance	Mediterranean climate of Spain	Daylighting, solar shading	Side window, light transmittance 78%
Chi et al., (2016)	Perforation percentage, shape, orientation, matrix	Mediterranean climate of Spain	Daylighting	Side window, light transmittance 78%

Integration of Perforated Screen Façade and Reflective Light Shelves

Although the daylight level is high all year in the tropics, using shading devices is essential since the design emphasis typically avoids overheating by limiting the amount of daylight in the building (IEA in Elsiana et al., 2021). PSF is one type of shading system that can prevent direct solar radiation from entering the building while still providing daylight and view (Srisamranrungruang and Hiyama, 2020). Previous research showed that a smaller perforation percentage results in lower daylight and overlit areas. Perforated screens must have higher perforation percentage to achieve higher daylight levels in the areas farther from the building perimeter (Sherif et al., 2012a).

Integrating a perforated screen facade (PSF) as a shading system and a light shelf (LS) as a daylighting system, which can reflect daylight to the ceiling and enhance daylight distribution, is proposed to improve daylight performance. Integrating daylighting and shading systems can enhance the daylight performance of buildings in the tropics (Elsiana et al., 2021). The study aims to evaluate the daylight performance of PSF and LS integration in an office building in the tropics.

METHODS

The experimental research method uses Integrated Environment Solution-Virtual Environment (IES-VE) Radiance IES daylight simulation as a tool. IES-VE is a combined model where building performance simulation and the design tool are in the same environment (Negendahl, 2015). IESVE is reliable, stable, and built upon the validated building performance simulation results. It employs a Radiance-based engine and uses a raytracing calculation method.

The validation of IES-VE for studying daylight performance in buildings has been extensively demonstrated in previous research. These studies have covered numerous daylighting systems, including horizontal light pipes and shading systems (Elsiana et al., 2023a), anidolic daylighting systems (Roshan and Barau, 2016), dynamic internal LS (Lim and Heng, 2016), and horizontal light pipes (Heng et al., 2020). The consistent findings of these studies underscore IES-VE's reliability in simulating the daylight performance of numerous systems under tropical sky conditions.

The simulation uses weather data for Surabaya (latitude 7°37'S and longitude 112°78' E). Figure 1 shows the sun path diagram of Surabaya. The highest probability of occurrence of sky conditions in Surabaya is intermediate sky conditions, followed by clear and overcast sky conditions (Elsiana et al., 2023b). Average Daylight Factor (DFavg), Useful Daylight Illuminance (UDI), and Daylight Glare Probability (DGP) of an office room with a side window (base case) were compared with an office room with LS (case 1), room with PSF (case 2), and room with PSF and LS (case 3).

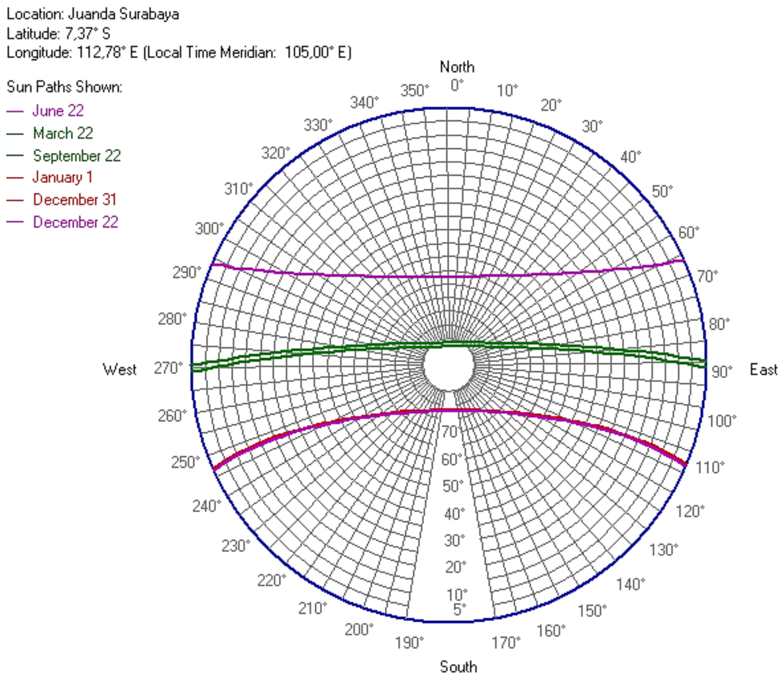


Fig. 1. Sunpath Diagram of Surabaya in IES-VE Radiance IES 2023

Office Room with Perforated Screen Facade and Light Shelf

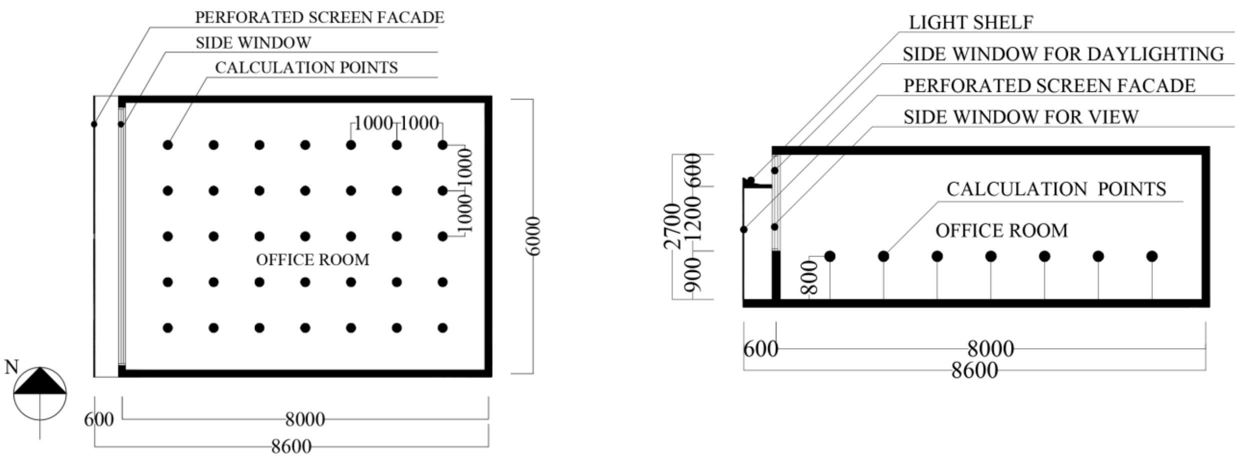
The office space with PSF and LS was created in Model IT in IES-VE. The office space was 6 m in width and 8 m in depth, representing a medium-depth office space. The ceiling height was 2.7 m, while the windowsill height was 0.90 from the floor level.

The window was divided into a daylighting window and a window for view. The height of the window head for the view was 2.10 m from the floor. The upper part was a window for daylighting, as seen in Figure 2 and Figure 3. The side window faced the West and had a window-to-wall ratio of 60.58%. The material of the side window glazing was clear glass with a visible transmittance of 85%. The material properties of the office space and side window are shown in Table 2.

A perforated screen facade is applied as a second skin facade and functions as a shading system. The perforated screens used in the experiment were circular in shape and had a radius of 0.08 m, as shown in Figure 4. The perforated percentage was 40%, which aligns with the recommended perforated screen percentage for acceptable daylight with no disturbing glare by Srisamranrungruang and Hiyama (2020). PSF had a reflectance of 83% and was situated at a distance of 0.60 m from the side window.

The side window was divided into a window for daylighting and a window for view. The external LS depth was 0.60 m and was installed at a height of 2.10 m from the floor. It had a fixed inclined reflector to redirect sunlight with changing sun altitudes. The upper surface of the LS was reflective material, which has a reflectance of 80%. Figures 2 and 3 show the plan, section, and perspective of an office room with a perforated screen façade and light shelf. Figure 5 shows the plan of base case and cases.

The calculation points were set at a height of 0.8 m from the floor in a grid of 1x1 m. Glare calculations were performed at a single point, at the center of space, at a distance of 2 m from the side window. The camera height was 1.15 m above the floor, according to the eye level height in the sitting position of the building user. The simulation time was selected on critical dates throughout the year: equinox on 21 March and solstice on 21 June and December. For the side window facing west, the potential for glare occurred in the late afternoon since the sun altitude is relatively high in the tropics, such as Surabaya. Thus, the daylight glare probability (DGP) evaluation was simulated at 15:00. DGP is measured at 1.20 from the floor and 2.00 m from the side window.



(a) (b)

Fig. 2. (a) Plan and (b) Section of Office Room with Perforated Screen Facade and Light Shelf

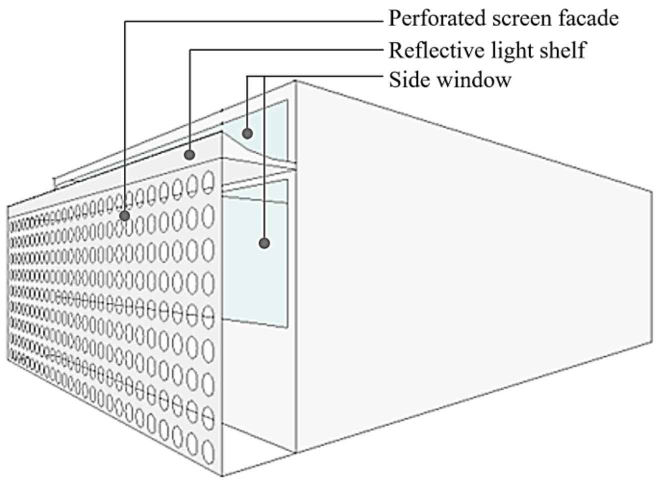


Fig. 3. Perspective of Office Room with Light Shelf and Perforated Screen Facade

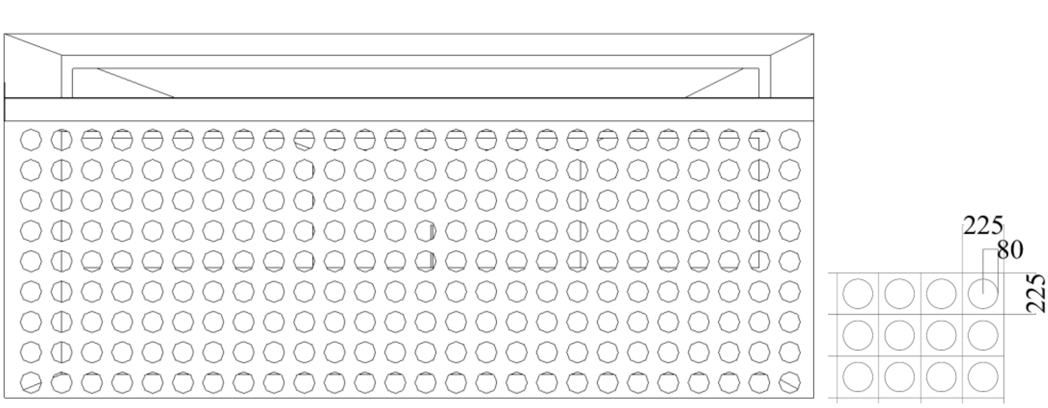
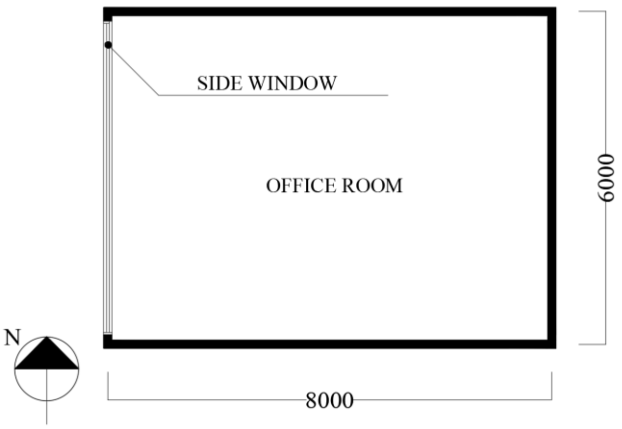
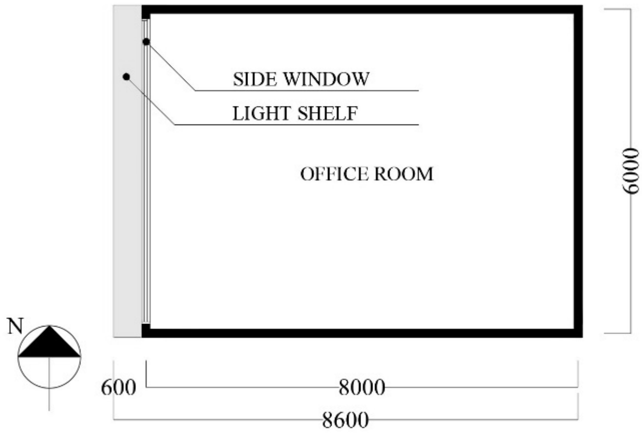


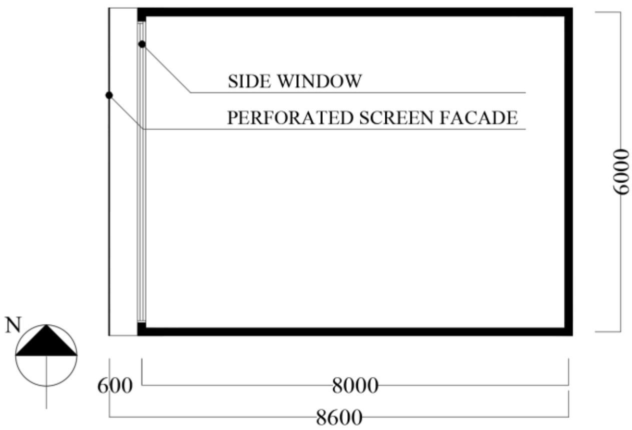
Fig. 4. The Dimension of Perforated Screen Facade



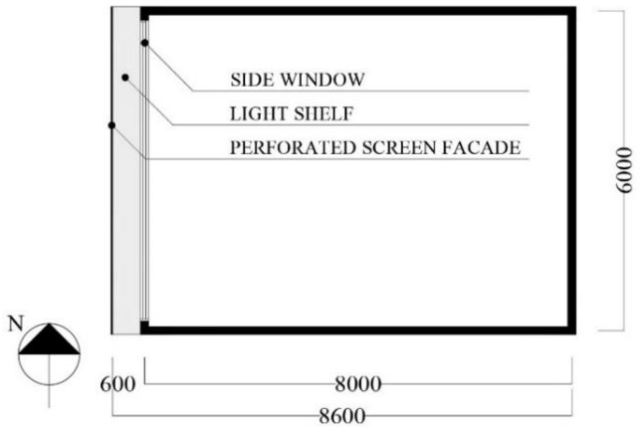
Base Case
Office room with side window



Case 1
Office room with side window and light shelf (LS)



Case 2
Office room with side window and perforated screen façade (PSF)



Case 3
Office room with side window, LS and PSF

Fig. 5. Plan of Base Case and Cases

Table 2. Material Properties of Office Room, Light Shelves, and Perforated Screen

Office Room	Specularity	Roughness	Reflectance	Transmissivity
Ceiling	0.80	0.00	0.00	N/A
Floor	0.00	0.005	0.42	N/A
Wall	0.80	0.00	0.00	N/A
Window glazing Clear float 6 mm	N/A	N/A	N/A	0.85
Upper surfaces of light shelf	0.90	0.02	0.80	N/A
Perforated screen	0.20	0.03	0.83	N/A

Daylight Performance Metrics

The following daylight metrics were examined to evaluate daylight performance: average daylight factor (DFavg), useful daylight illumination (UDI), and daylight glare probability (DGP). DF is still a useful daylight performance metric since an overcast sky could be considered as a "worst-case" scenario for daylighting design (Yu and Su, 2015). UDI is computed based on horizontal illuminance, while DGP is based on vertical illuminance and luminance contrast (Atthaillah, 2022).

The Daylight Factor is the ratio of average internal illuminance (Ei) to average external illuminance (Eo) multiplied by 100% (Szokolay, 2008). The average Daylight Factor (DFavg) is the average of DF at all calculation points in Figure 2. The recommended DFavg for an office workplace is 2-5% (British Council for Offices Guide in Alrubaih et al., 2013). Office rooms with DFavg greater than 5% appear very bright (McMullan, 2012). Recommended DF for ordinary visual tasks such as filling, reading, and easy office tasks is 1.5-2.5% (Stein in Alrubaih et al., 2013).

$$\mathrm{DF} = \frac{\mathrm{Ei}}{\mathrm{Eo}} \mathrm{x} 100\% \quad (1)$$

Where**:**
Ei = indoor illuminance
Eo = outdoor illuminance

Useful daylight illuminance (UDI) expresses the percentage of the occupied hours when daylight levels of the working plane are achieved between 100-3000 lx ($UDI_{100\text{-}3000lx}$). UDI range is then subdivided into UDI supplementary ($UDI_{100\text{-}300lx}$), where additional electric lighting still needed to complement daylight for common tasks such as reading; UDI autonomous ($UDI_{300\text{-}3000lx}$), where supplemental electric lighting most likely not be required (Mardaljevic et al., 2012); UDI exceed ($UDI_{>3000lx}$) where 3000lx threshold as an indicator of discomfort glare; and UDI fell short ($UDI_{<100lx}$) where commonly considered insufficient to be primary source of illumination or to significantly contribute to electric lighting (Nabil and Mardaljecvic, 2006).

$$\mathrm{UDI100-3000lx} = \frac{t_{100lx \le E < 3000lx}}{T} \mathrm{x100\%} \quad (2)$$

Where:
E = illuminance
t = duration in which daylight illuminance at workplane fulfills the designated range
T = total observation time in year

Daylight Glare Probability (DGP) is developed to assess glare from daylight and consider both luminance contrast and vertical illuminance on the observer's eye (Wienold and Christoffersen, 2006). DGP values less than 0.35 are perceived as imperceptible. DGP values between 0.35 and 0.40 are perceived as perceptible, between 0.40 and 0.45 are disturbing, and >0.45 are intolerable.

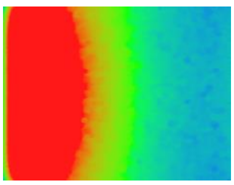
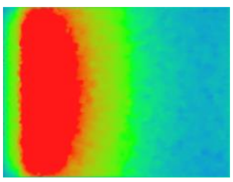
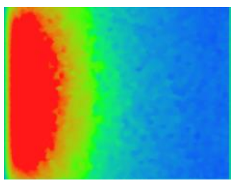
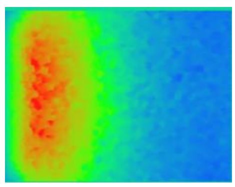
RESULTS AND DISCUSSION

Daylight Factor

The simulated DFavg for the base case and cases is shown in Table 3 and Figure 6. The base case, an office room with a side window, had the highest DFavg, as high as 4.33%, and was in the range of recommended DF for an office workplace. The second highest DFavg was obtained in case 1, the office space with a side window, and LS, which was as high as 3.37%. Case 2, room with side window and PSF, had a DFavg of 2.42%. The DFavg of cases 1 and 2 were also in the range of recommended DF for office workplaces. The lowest DFavg was obtained in case 3, the office space with a side window, PSF, and LS, as high as 1.95%. The DFavg of case 3 was slightly below the recommended DFavg for the office workplace. However, it still fulfilled the recommended DF for ordinary visual tasks.

The DFavg of all cases was lower than the base case. Under overcast sky conditions, using LS reduced the DFavg by a significant 22.2%. Similarly, integrating PSF in front of the glazing façade led to a substantial decrement in DFavg by 44.1%. The most significant reduction, however, was observed when both LS and PSF were used, resulting in a 55% decrease in DFavg.

Table 3. Daylight Factor of Base Case and Case

Daylight Factor	**Base Case** Office room with side window	**Case 1** Office room with side window and light shelf (LS)	**Case 2** Office room with side window and perforated screen façade (PSF)	**Case 3** Office room with side window, LS and PSF
				
average	4.33	3.37	2.42	1.95
Percentage of changes in DF_{avg} (%)		-22.20	-44.1	-55.00
Percentage of calculation points achieving DF range 2-5%	25.71	28.57	28.57	42.86

Under overcast sky conditions, the highest DF for the base case was 12.3% at a sensor point 1 m from the side window. This high DF level underscores the unsuitability of office rooms without any shading devices and clear glazing in the tropics. Office rooms with a DFavg of more than 5% are perceived as very bright (McMullan, 2012), a condition that is not conducive to productive work. These findings align with the previous research of Lim and Heng, 2016, which also highlighted the excessively high daylight levels in office buildings without proper external shading in the tropics.

The use of LS reduced the highest DF to 32.5%, while the use of PSF lowered the highest DF to 34.96%. The highest DF level of the office room with LS (case 1) and the one with PSF (case 2) are still more than 5%, meaning they appear very bright. Room with the integration of LS and PSF (case 3) that had the highest DF of less than 5% and had fulfilled the recommended DF for the office workplace. The combination of LS and PSF gives the most significant decrement of the highest DF, as high as 61.79%.

Figure 7 shows the percentage of calculation points that have DF 2-5%. The results showed that the highest percentage of calculation points with a DF value of 2-5% was case 3, as high as 43%. The lowest percentage of calculation points with a DF value of 2-5% was the base case, as high as 26%. The percentage of calculation points with DF value 2-5% in case 1 and case 2 was 29%.

These findings demonstrated the role of external LS in reflecting daylight toward the ceiling and providing shading. These results also showed the effectiveness of PSF as a shading system by reducing the DFavg and the excessive DF in the area close to the side window. These results are aligned with previous studies about the impact of LS use in reducing the daylight level (Ochoa and Capeluto, 2006).

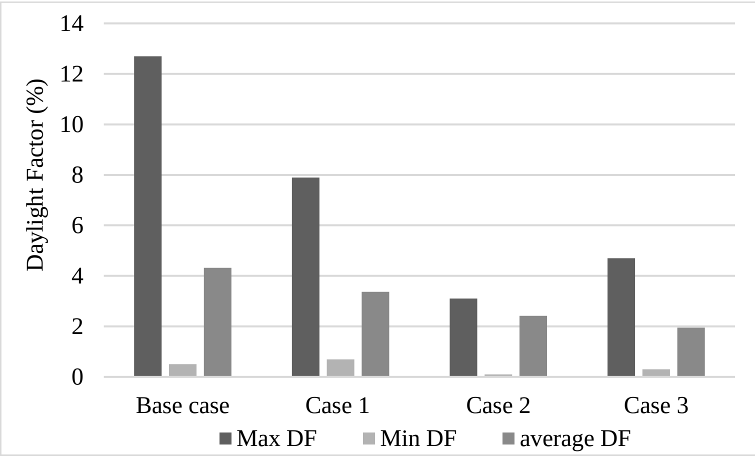


Fig. 6. Maximum, Minimum, and Average Daylight Factor of Base Case and Cases

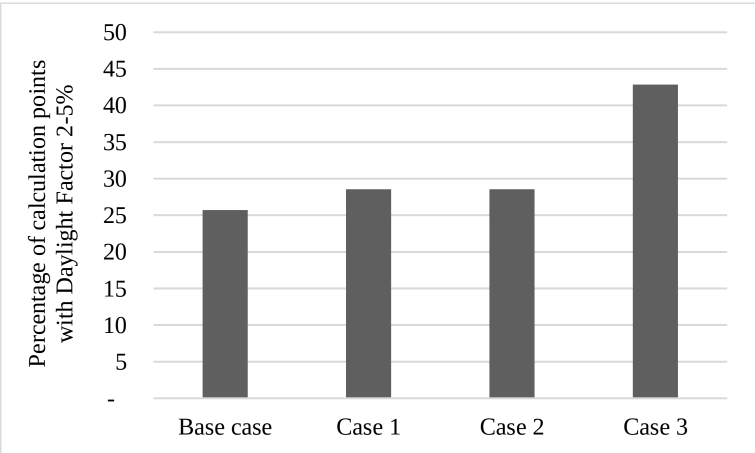


Fig. 7. Percentage of Calculation Points of Base Case and Cases with Daylight Factor 2-5%

Useful Daylight Illuminance

Figure 8 displays the UDI of the base case and cases. Results showed that the base case had the lowest $UDI_{100-3000lx}$, as high as 70%. The base case also had the highest percentage of occupied hours in the year, with $illuminance_{>3000lx}$, as high as 30%. Daylight illuminance of more than 3000 lx creates either thermal or visual discomfort. This finding is aligned with earlier studies on high illuminance by large, glazed façade buildings in the tropics (Lim and Heng, 2016).

Introducing an exterior Light Shelf (LS) in office space significantly reduced $UDI_{>3000lx}$ by 23.3%. LS also enhanced the $UDI_{100-3000lx}$, increasing it by 10%. The $UDI_{>3000lx}$ and UDI 100-3000lx of office space with LS were 23% and 77%, respectively. There were no instances of the illuminance falling below 100lx or between 100-500lx throughout the year.

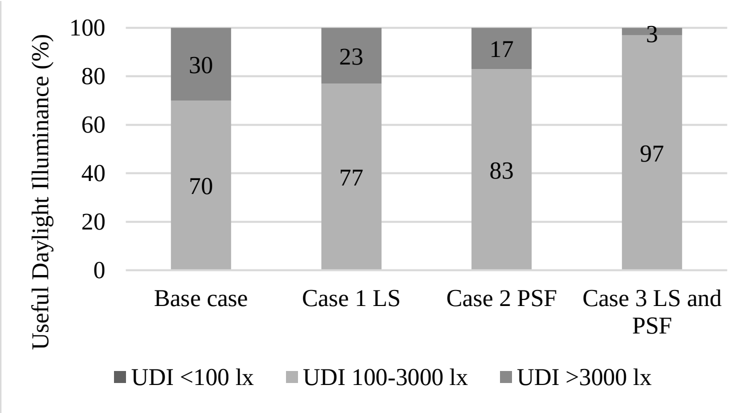


Fig. 8. Useful Daylight Illuminance of Base Case and Cases

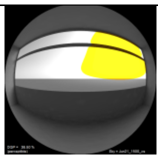
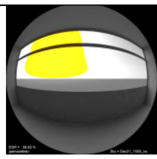
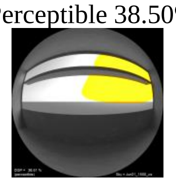
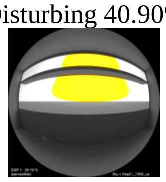
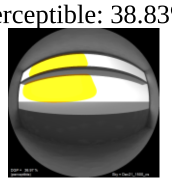
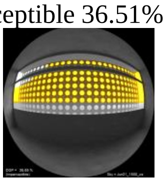
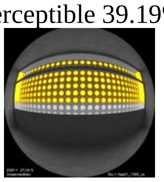
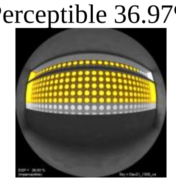
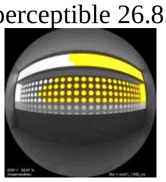
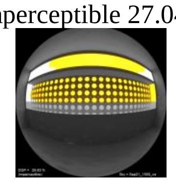
The $UDI_{>3000lx}$ of a room with PSF was 17%. The use of PSF in front of a glazed façade led to a significant reduction in the $UDI_{>3000lx}$ by as much as 43.3% compared to the base case. These results demonstrate the effectiveness of PSF in controlling high illuminance levels. The office room with PSF also showed a substantial improvement in the $UDI_{100-3000lx}$, reaching 83%. These results highlight the positive impact of PSF, with the $UDI_{100-3000lx}$ reaching 18.57%.

Integration of PSF and RLS improved the $UDI_{100-3000lx}$ as high as 38.57%. The $UDI_{100-3000lx}$ of case 3 was the highest among all cases and reached 97%. Integration of PSF and LS significantly decreased the $UDI_{>3000lx}$, as high as 90%. The $UDI_{>3000lx}$ of office room with PSF and LS was only 3%.

Daylight Glare Probability

The results showed that on 21 June and 21 December, the office room with side window had a Daylight Glare Probability (DGP) of 38.50% and 38.83%, respectively, which is perceptible by building users (Table 4). On 21 September, the DGP of the room with a side window reached 40.90%, which is in the range of disturbing for building users. These results align with Lim and Heng, 2016, where a window facing west in the tropics has a glare problem without shading.

Table 4. Daylight Glare Probability of Base Case and Cases

	Daylight Glare Probability		
	21 June	21 September	21 December
Base case Office room with side window	 Perceptible 38.50%	 Disturbing 40.90%	 Perceptible: 38.83%
Case 1 Office room with side window and light shelf	 Perceptible 36.51%	 Perceptible 39.19%	 Perceptible 36.97%
Case 2 Office room with side window and perforated screen facade	 Imperceptible 26.85%	 Imperceptible 27.04%	 Imperceptible 26.60%
Case 3 Office room with side window, perforated screen façade and light shelf	 Imperceptible 28.81%	 Imperceptile 29.83%	 Imperceptible 29.14%

Under clear sky conditions, the room with a side window and LS has a DGP in the range of 36.1-39.19%, which was perceptible by the building user. The use of LS alone reduced the DGP, but in this case, it was still perceptible by building users, in the range of 36.51% on 21 June to 39.19% on 21 September. Integrating LS alone on the window facing west decreased the DGP, but it was still perceptible by building users.

The introduction of PSF in the office room had a significant impact on reducing the DGP. The perceptible glare that was evident in the base case (a room with a side window and no shading) on 21 June (DGP 38.5%) was rendered imperceptible (DGP 26.85%) with the use of PSF. Similarly, the disturbing glare in the base case on 21 September (DGP 40.90%) became imperceptible (DGP 27.04%) with the integration of PSF. The perceptible glare in the base case on 21 December also became imperceptible (DGP 26.60%) with the use of PSF in the office room.

The integration of PSF and LS reduced the DGP. The perceptible glare in the base case on 21 June (DGP 38.5%) became imperceptible with a DGP of 28.81%. The disturbing glare present in the base case on 21 September with a DGP of 40.9% becomes imperceptible by a DGP of 29.83%. The perceptible glare present in the base case on 21 December with a DGP of 38.83% becomes imperceptible with a DGP of 29.14%. In this research, LS on a window facing west must be combined with other shading systems, such as PSF, to avoid glare.

CONCLUSION

This work evaluates the daylight performance of integrating the perforated screen façade (PSF) as a shading system and light shelf (LS) as a daylighting system. The study examined three daylight performance metrics: Daylight Glare Probability (DGP), Useful Daylight Illuminance (UDI), and Average Daylight Factor (DFavg). The results demonstrated that integrating PSF and LS improved daylight performance by lowering the DFavg by 55%, increasing the $UDI_{100\text{-}3000lx}$, and reducing the DGP to imperceptible by building users. The combination also results in the most significant decrement in the highest DF, 61.79%, and fulfills the recommended DF for the office workplace.

This result implies significant improvement in daylight performance, both daylight intensity under overcast sky conditions through the Daylight Factor, the annual occurrence of daylight illuminances within a specific range through UDI, and visual comfort through DGP. Integrating PSF as a shading system and LS as a daylighting system is essential in the Tropics.

Future research will focus on optimizing PSF in integration with LS for daylighting performance. More studies on the view inside the building resulting from different perforated aspect ratios of PSF are also needed. Furthermore, it is also essential to study the thermal and energy performance of the combination of PSF and LS in buildings in the tropics.

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