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OPTIMIZATION OF ASYMMETRIC BILATERAL COMPLEX FENESTRATION SYSTEMS IN STATE ELEMENTARY SCHOOL CLASSROOMS IN INDONESIA

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Abstract_ *Penelitian ini bertujuan untuk meningkatkan kinerja pencahayaan alami siang hari (PASH) dengan menggunakan sistem penetrasi kompleks (CFS) bilateral asimetris di ruang kelas hipotetis yang terletak di dua kota tropis di Indonesia, yaitu Bandung dan Lhokseumawe, yang masing-masing terletak di sebelah selatan dan utara garis khatulistiwa. Bandung merupakan kota tropis diatas pegunungan, sedangkan Lhokseumawe merupakan kota pesisir. Optimalisasi dilakukan untuk keempat orientasi mata angin. Kinerja PASH ruang kelas dinilai dengan menggunakan metrik* $aUDI_{250\text{-}750lx}$*,* $aUDI_{100\text{-}3000lx}$*,* $sDA_{300/50\%}$*, dan* $ASE_{1000.250}$*. Kondisi awal menunjukkan performa pencahayaan siang hari yang tidak memadai ditunjukkan oleh nilai* $aUDI_{100\text{-}3000lx}$ *yang rendah (di bawah 80%) dan nilai* $ASE_{1000,250}$ *yang tidak memuaskan (di atas 10%). Untuk memenuhi standar performa pencahayaan siang hari yang baik, penelitian ini menggunakan metode simulasi komputasi untuk kondisi tahunan. Selanjutnya, algoritma RBFOpt digunakan melalui Opossum untuk melakukan optimasi. Berdasarkan hasil optimasi, integrasi CFS ke dalam selubung bangunan menghasilkan peningkatan kinerja PASH di kedua lokasi.*

Keywords: *Penetrasi kompleks; Pencahayaan alami siang hari; Bukaan asimetris; Optimasi.*

Abstrak_ This study aims to enhance the daylighting performance of an asymmetric bilateral complex fenestration system (CFS) in a hypothetical classroom located in two Indonesian tropical cities, namely Bandung and Lhokseumawe, which are located slightly south and north of the equator, respectively. Bandung is a mountainous tropical city, whereas Lhokseumawe is a coastal city. Optimization is conducted for all four cardinal orientations. The classroom's daylight performance is assessed using $aUDI_{250\text{-}750lx}$, $aUDI_{100\text{-}3000lx}$, $sDA_{300/50\%}$, and $ASE_{1000,250}$ metrics. The baseline conditions reveal inadequate daylighting performance with a low $aUDI_{100\text{-}3000lx}$ reading (below 80%) and an unsatisfactory $ASE_{1000,250}$ value (above 20%). To meet the good daylighting performance standards, this study utilizes a computational simulation method for annual daylight simulation. Furthermore, the RBFOpt algorithm was used through Opossum to conduct optimization. According to the optimization results, the integration of CFS into the building's envelope results in improved daylight performance in both locations.

Kata kunci: Complex fenestration; Daylighting; Asymmetrical bilateral opening; Optimization.

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INTRODUCTION

The most common type of school in Indonesia is the government-funded primary school (SDN), which accounts for 67% of all schools in Indonesia (Kemdikbud, 2020). In SDN classrooms, there are openings or fenestrations, most of which are bilaterally symmetrical, i.e., light openings on two opposite sides have the same shape and size (Kementerian Pendidikan Nasional RI, 2011). The purpose of this opening, or fenestration, is to allow daylight to enter the classroom. Daylight plays a crucial role in designing buildings, including schools. The utilization of daylight can reduce a building's energy consumption by approximately 40-45% (Ander, 2016; Lechner, 2007; Mediastika, 2013). Building envelope design contributes the most to energy savings, with 71% compared to other factors like occupant behavior, equipment usage, and artificial lighting (Primanti et al., 2020). Hence, daylighting has a significant effect on energy conservation.

Several studies on SDN have utilized the Daylight Factor (DF) static measurement metric to directly measure illuminance values within a specific time frame (Idrus, Ramli Rahim, et al., 2019; Wibowo et al., 2017). Previous studies found that most school classrooms did not meet the criteria for good daylight (Atthaillah & Bintoro, 2019a, 2019b; Idrus, Rahim, et al., 2019; Wibowo et al., 2017). The distribution of annual illuminance was assessed solely using the daylight metric in Lhokseumawe, indicating insufficient availability of daylight in the mentioned area (Atthaillah & Bintoro, 2019a, 2019b). A study examined the impact of direct sunlight on classrooms and discovered that about 43% of the 250 classrooms investigated were affected by direct sunlight. This could potentially cause overheating in the classrooms (Atthaillah, Mangkuto, & Koerniawan, 2022). Another study investigated the potential of external horizontal shading devices and window-to-wall ratio (WWR) as input parameters. However, glare potential was still present in the room during some of the study hours (Atthaillah, Mangkuto, Koerniawan, & Yuliarto, 2022; Atthaillah et al., 2023).

Additionally, exposure to daylight has been shown to enhance the well-being and productivity of occupants, as it impacts various biological, psychological, and physiological factors. Daylight has been shown to have various positive effects, including improving mood, increasing energy, reducing toxic mold present in humid rooms, suppressing the hormone melatonin to enhance focus, improving blood circulation, and boosting occupant immunity (Bahdad et al., 2020; Bakmohammadi & Noorzai, 2020; Boubekri, 2008; Boubekri et al., 2020; Heschong et al., 2000; Mediastika, 2013; Shishegar et al., 2021). Daylighting impacts the human hormone melatonin, which in turn affects productivity, a crucial aspect of school activities. However, Indonesia might experience excessive sunlight due to its location at 6 °LU - 11°LS and 95°BT - 141 °BT, leading to undesired effects such as thermal and visual discomfort in buildings (Tabadkani et al., 2018).

In order to obtain an optimal classroom in the tropics one potential approach is to design a bilateral asymmetric complex fenestration system (CFS) since the value of solar radiation in each orientation is also different. CFS is a fenestration system (light openings) that uses complex shading, which can reflect incoming sunlight repeatedly and, in many directions (de Vries et al., 2021; Decia et al., 2019; Mashaly et al., 2021). Previous research recommends using interior blinds as a mitigation strategy for improving interior daylight (Mangkuto et al., 2022). Next, The method used for the optimization of the CFS is a single-objective optimization which is called radial basis function optimization (RBFOpt) where this algorithm produces good optimization results quickly and robustly (R. M. Sakiyama et al., 2021). Therefore, the purpose of this study was to determine the optimum design of bilateral asymmetric CFS for application in classrooms in some orientations of SDN in Indonesia.

METHOD

This study evaluates a hypothetical classroom located in above the equator (Bandung) and below the equator (Lhokseumawe), Indonesia. This classroom is 8.0 m × 7.5 m × 3.5 m with bilateral symmetric opening types (Kementerian Pendidikan Nasional RI, 2011), as shown in Figure 1.

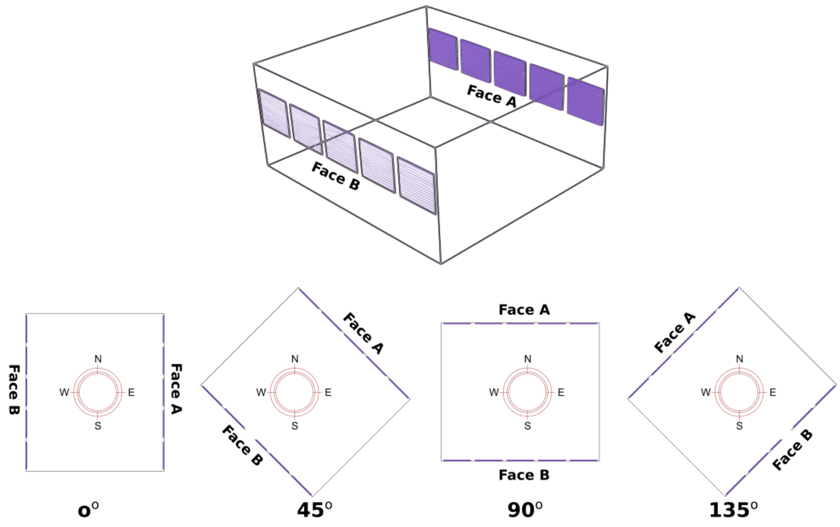

Figure 1 Classroom model (upper row) and evaluated orientation (bottom row).

The study utilized a computational simulation method to optimize window orientations, namely 0°, 45°, 90°, and 135°, using bilateral asymmetric CFS. To ensure accuracy, blinds were installed on the window's interior. The *Rhinoceros* platform (Robert McNeel & Associates, 2019), in conjunction with *Grasshopper* (Rutten, 2010) and *Honeybee* [+] (Roudsari & Pak, 2010; Subramaniam, 2017) for accessing *Radiance* (Ward & Rubinstein, 1988), was employed. The study utilized several design parameters to optimize the outcomes. These parameters included the window-to-wall ratio (WWR), blind-to-window ratio (BWR), blind type, slat width, slat separation to width ratio, and slat angle. Table 1 displays the range of these values. The design parameters for optimization included the window to wall ratio (WWR), blind to window ratio (BWR), blind type, slat width, slat separation to width ratio, and slat angle.

Radiance is a reliable simulation engine for conducting daylight simulations, which has undergone long-term (Mardaljevic, 2000; Reinhart & Walkenhorst, 2001) and short-term validation (Atthaillah, Mangkuto, Koerniawan, Hensen, et al., 2022; Bahdad et al., 2020; Khidmat et al., 2022) by various researchers worldwide. Additionally, Radiance is capable of calculating scenes within buildings integrated with CFS (Brembilla et al., 2019; Geisler-Moroder et al., 2017; McNeil & Lee, 2012). Therefore, it is a reliable tool to perform daylight simulations in accordance with this research.

Table 1. Design (input) parameters values

Parameters	Variation of parameters value	Remarks
WWR	0.15 – 0.30	0.15 means 15% of window to wall ratio on one side of wall consisting of window(s).

Parameters	Variation of parameters value	Remarks
BWR	0.25 – 1.00	A value of 0 (zero) means no coverage and 1 (one) means full coverage of the blind on the inside of the window.
Blind Type	Horizontal and Vertical	Type of blind slat design.
Slat Width (mm)	30 mm – 70 mm	The width of each slat of the blind.
Space to Width Ratio	0.8 – 1.0	The ratio between the width of the slat and its spacing.
Slat Angle (˚)	−60˚ – 60˚	For a horizontal type of blind, a negative angle means that the slats are opened to the top, while a positive angle means that the slats are opened to the bottom. For vertical type blind, a negative angle means that the slats are opened according to clockwise direction and vice versa.

The output parameters that represent the daylighting performance in classrooms were $aUDI_{250\text{-}750lx}$, $aUDI_{100\text{-}3000lx}$, $sDA_{300/50\%}$, and $ASE_{1000,250}$. Useful daylight illuminance (UDI) was a metric that reveals the percentage of illuminance measured within a specific range of illuminance at a specific location for one year, indicating if there was sufficient or insufficient daylighting. This illuminance range identified whether lighting at a particular point was appropriate, not excessive or too dim (Nabil & Mardaljevic, 2005). This study utilized the illuminance range advocated by the Indonesian national standards for classrooms, specifically, 250-750 lux (Badan Standardisasi Nasional (BSN), 2000) and 100-3000 lux (Mardaljevic et al., 2011) for UDI. The spatial value obtained was the average of UDI which in this study was called $aUDI_{250\text{-}750lx}$ and $aUDI_{100\text{-}3000lx}$ respectively.

Spatial daylight autonomy (sDA) is a metric that measures the spatial distribution of daylight within a space and is calculated based on daylight autonomy (DA) values. DA represents the percentage of time that a point in a space received daylight with an illuminance level of 300 lux or more over the course of a year (Reinhart & Walkenhorst, 2001). sDA, on the other hand, is a spatial percentage that indicates the proportion of points in a room that receive at least 50% of the total measurement time with a DA value of 300 lux or more ($sDA_{300/50\%}$). Annual Sunlight Exposure (ASE) is a metric that measures the amount of direct sunlight exposed over a year. The definition of ASE is the percentage of the room or measuring point that receives equal to or more than 1000 lx of direct sunlight for 250 hours within a year ($ASE_{1000,250}$) (United States Green Building Council (USGBC), 2017).

The optimal input variation to achieve the highest daylighting performance was selected based on the variations of the CFS parameters employed. The single objective method used in this research employed the radial basis function optimization (RBFOpt) algorithm, which was accessible through the Opossum plug-in in Grasshopper. The single objective method is an optimization approach that focuses on minimizing or maximizing a single objective value. The RBFOpt algorithm was developed for the construction of an approximation model and its iterative refinement for an unknown cost function using a sample value (Costa & Nannicini, 2018). The objective function for this optimization process included four optimization outputs: $aUDI_{250\text{-}750lx}$, $aUDI_{100\text{-}3000lx}$, $sDA_{300/50\%}$, and $ASE_{1000,250}$, as shown in equation (1).

$$f = aUDI_{250-750lx} + aUDI_{100-3000lx} + sDA_{300,50\%} - ASE_{1000,250} \quad (1)$$

Equation (1) aims to optimize daylighting performance in a given space by maximizing the values of $aUDI_{250\text{-}750lx}$, $aUDI_{100\text{-}3000lx}$, and $sDA_{300/50\%}$ while minimizing the value of $ASE_{1000,250}$. The goal is to achieve daylighting that is neither insufficient nor excessive with uniform distribution and without excessive direct sunlight.

RESULT AND DISCUSSION

Based on the simulation result, the classroom with baseline conditions where CFS has not been installed, the performance of daylighting is obtained, which is shown in Table 2 and Figure 2.

Table 2. Daylight performance in classroom for the baseline

Orientation	Daylight Parameters	Value in Lhokseumawe	Value in Bandung
0°	$UDI_{100\text{-}3000lx}$	57.3%	62.25%
0°	$sDA_{300/50\%}$	100%	100%
0°	$ASE_{1000,250}$	89.2%	68.2%
45°	$UDI_{100\text{-}3000lx}$	62.4%	67.5%
45°	$sDA_{300/50\%}$	100%	100%
45°	$ASE_{1000,250}$	48.7%	43.6%
90°	$UDI_{100\text{-}3000lx}$	68.9%	71.9%
90°	$sDA_{300/50\%}$	100%	100%
90°	$ASE_{1000,250}$	23.1%	23.1%
135°	$UDI_{100\text{-}3000lx}$	62.6%	66.9%
135°	$sDA_{300/50\%}$	100%	100%
135°	$ASE_{1000,250}$	49.2%	40.6%

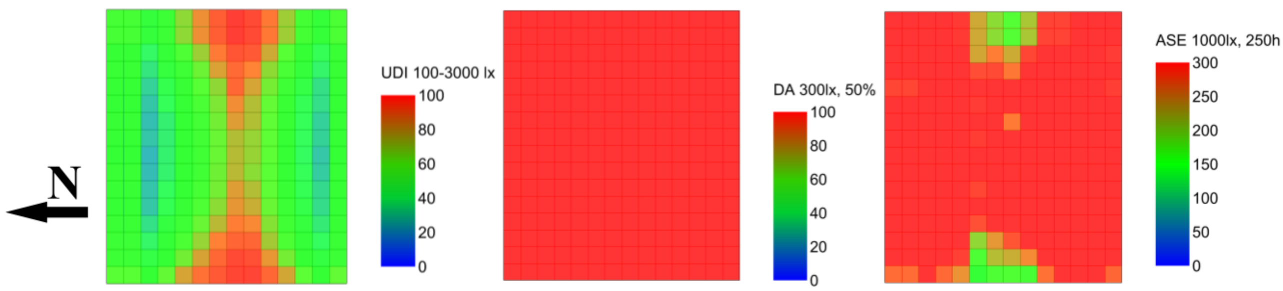

Figure 1. Daylight Spatial Condition in the Classroom for Baseline Condition

The simulation results showed that the $aUDI_{250\text{-}750lx}$ value in each orientation was relatively low and less than 80%, that it did not meet the criteria. The $sDA_{300/50\%}$ value in each orientation was 100% and more than 80% so it met the criteria. The $ASE_{1000,250}$ value in each orientation was relatively high, which was more than 20%, so it did not meet criteria (≤ 20%). The area near the window showed excessive daylight, hence, it must be further optimized.

Furthermore, the optimization of the building design was carried out by installing CFS as a building design parameter with a bilateral asymmetric shape, where opposite sides have different CFS parameters. The optimization was performed using the RBFOPT algorithm in Grasshopper. The optimization was performed to find the most optimal CFS parameters for each orientation in each city. Initially 1000 iterations were performed in Lhokseumawe at orientations 0° and 90°, but since the objective value has started to converge at 400 iterations, thus, this study conducted 500 iterations in other orientations to save time. The optimization result for input and output variables for both locations are shown in Table 3 to Table 6.

Table 3. Optimum Input Parameters in Lhokseumawe

Orientation	WWR	BWR	Left				Right			
			Type	Slat Width (mm)	Space to width Ratio	Slat Angle (°)	Type	Slat Width (mm)	Space to width Ratio	Slat Angle (°)
0°	0.15	1.00	V	50	1.0	−60	V	70	10	−30
45°	0.15	1.00	V	30	0.8	−30	H	30	8	60
90°	0.15	1.00	H	70	0.9	0	V	70	9	30
135°	0.15	1.00	V	70	1.0	−30	V	70	10	−45

Table 4. Optimum output variables in Lhokseumawe

Orientation	$aUDI_{250\text{-}750lx}$ (%)	$aUDI_{100\text{-}3000lx}$ (%)	$sDA_{300/50\%}$ (%)	$ASE_{1000,250}$ (%)	f (%)
0°	71.5	97.5	99.5	10.3	258.2
45°	54.6	95.5	57.4	5.6	201.9
90°	78.1	99.3	100	5.6	271.7
135°	74.0	98.3	100	5.6	266.7

Table 5. Optimum input parameters in Bandung

Orientation	WWR	BWR	Left				Right			
			Type	Slat Width (mm)	Space to width Ratio	Slat Angle (°)	Type	Slat Width (mm)	Space to width Ratio	Slat Angle (°)
0°	0.15	0.75	V	30	0.8	−60	V	70	0.8	60
45°	0.15	0.75	V	30	0.8	−30	H	40	1	45
90°	0.30	1.00	H	30	0.9	60	H	60	1	−45
135°	0.15	1.00	H	60	1.0	0	H	70	10	30

Table 6. Optimum Output Variables in Bandung

Orientation	$aUDI_{250-750lx}$ (%)	$aUDI_{100-3000lx}$ (%)	$sDA_{300/50\%}$ (%)	$ASE_{1000,250}$ (%)	*f* (%)
0°	**65.7**	**88.8**	**94.4**	**10.3**	**238.6**
45°	**67.4**	**90.1**	**100**	**11.8**	**245.7**
90°	**73.4**	**88.9**	**100**	**15.4**	**247.0**
135°	**74.5**	**89.9**	**100**	**9.7**	**254.6**

Based on the findings from Tables 4 and 6, it is evident that certain daylighting criteria have been met for each orientation in both cities. Specifically, $aUDI_{100-3000lx}$ exceeds 80%, $sDA_{300/50\%}$ is above 55%, and $ASE_{1000,250}$ is less than 20%. Considering the direct contribution of sunlight inside the classrooms, the optimal design in Lhokseumawe exhibits a comparatively minimal value when compared to Bandung which is represented by $ASE_{1000,250}$ values. However, $aUDI_{250-750lx}$ still falls short of the requirement of ≥ 80%. In Lhokseumawe, the highest $aUDI_{250-750lx}$ value is observed at 90° orientation, with a value of 78.1%. Meanwhile, in Bandung, the highest value of $aUDI_{250-750lx}$ is recorded at 130° orientation, with a value of 74.5%. The minimum $aUDI_{250-750lx}$ values in Lhokseumawe and Bandung were 45.6% and 65.7%, respectively, at orientations of 45° and 0°.

The optimal solution indicates that in Lhokseumawe, the WWR values are 15% for all orientations. In Bandung, the majority of orientations have similar WWR values, except for orientation 90°, which calls for a larger WWR (30%). As for the blind's parameters, there are no symmetrical values for the opposing window facades at any of the orientations examined in both cities. The majority of blinds in Lhokseumawe are of the vertical type (V), whereas in Bandung, horizontal blinds (H) are preferred for most of the orientations on both facades. In Lhokseumawe, the fully covered blind is recommended with a BWR of 1.00 at all orientations. In contrast, in Bandung, a BWR of 0.75 is recommended at 0° and 45° orientations, while fully covered is preferred at 90° and 135° orientations.

Based on the optimal solutions, the classroom equipped with CFS alone can meet specific daylighting standards, including $aUDI_{100-3000lx}$, $sDA_{300/50\%}$, and $ASE_{1000,250}$. However, when seeking greater uniformity, such as for a shorter daylight illuminance range (i.e., $aUDI_{250-750lx}$), none of the optimal solutions meet the criteria of ≥ 80% in both locations and all orientations. External shading may still be necessary (Atthaillah, Mangkuto, Koerniawan, & Yuliarto, 2022) despite the presence of internal CFS, such as blinds, in the classroom. Combining the two approaches could enhance the overall daylighting performance of the classroom. However, additional research is necessary to gain a more comprehensive understanding of the situation.

CONCLUSION

This study analyzed the daylight performance of a classroom with bilateral openings in the tropical climate, focusing on two Indonesian locations: Lhokseumawe and Bandung. The optimal design solutions indicate that different CFS configurations are required on opposing facades to achieve an optimal solution that incorporates various climate-based daylight metrics, as previously discussed. Although the optimal solution has improved for most daylight performance criteria,

$aUDI_{250\text{-}750lx}$ still exhibits underperformance (≤ 80%). Hence, it is necessary to investigate optimal daylight performance by integrating CFS with external shading devices.

In regards to input parameters, it is suggested that for values of 0.15 and 1.00, WWR and BWR respectively be utilized in Lhokseumawe. In contrast, for most orientations in Bandung, it is recommended that WWR be set to 0.15, except for orientation 90°. Additionally, in Bandung, it is advised to implement two BWR values of 0.75 and 1.00 for the aforementioned orientation conditions. Based on the fitness values, the orientation yielding the highest value in Lhokseumawe is 90°, whereas in Bandung it is 135°.

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