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Building Envelope Design Optimization of a Hypothetical Classroom Considering Energy Consumption, Daylight, and Thermal Comfort: Case Study in Lhokseumawe, Indonesia

Fahmi Nur Hakim[1], Yana Muhamadinah[1], Atthaillah[2,3*], Rizki A. Mangkuto[4], Anugrah S. Sudarsono[4]

[1]*Engineering Physics Master Program, Faculty of Industrial Technology Institut Teknologi Bandung, Jl. Ganesha 10, Labtek VI, Bandung 40132, Indonesia*
[2]*Engineering Physics Doctorate Program, Faculty of Industrial Technology Institut Teknologi Bandung, Jl. Ganesha 10, Labtek VI, Bandung 40132, Indonesia*
[3]*Architecture Program, Faculty of Engineering, Universitas Malikussaleh, Jl. Cot Teungku Nie, Aceh Utara 24355, Indonesia*
[4]*Building Physics Research Group, Faculty of Industrial Technology, Institut Teknologi Bandung, Jl. Ganesha 10, Labtek VI, Bandung 40132, Indonesia*

Abstract. This study evaluated the building performance of a hypothetical elementary school classroom considering its annual energy consumption, daylight criteria, and adaptive thermal comfort in Lhokseumawe, Indonesia. Variations in building materials, construction, and horizontal shading features were evaluated for the most optimal design solution. The aim was to optimize the multi-performance criteria as an integrated sustainable design solution for a typical classroom in Indonesia. To achieve this objective, the study utilized a computational simulation method using *Rhinoceros, Grasshopper*, and *Ladybug Tools* platforms. The optimization was conducted with *Galapagos*, an engine based on a genetic algorithm. The results suggest that the optimal solution achieved 100% $\text{sDA}_{300/50\%}$ and more than 96% $\text{UDI}_{100\text{-}3000\text{lx}}$. The annual thermal comfort percentage was also increased to over 90%, while the energy consumption was reduced by 20% compared to the baseline design.

Keywords: Design optimization; Hypothetical classroom; Integrated building design

1. Introduction

Designing a sustainable building is a complicated process that involves the consideration of the needs of building occupants, the building environment, aesthetics, and functional elements (Gharouni Jafari et al., 2021). A school classroom is an example of a building space where all of the performance criteria are necessary to ensure effective learning processes and outcomes among the students, particularly in elementary schools, where students are the most sensitive (Boubekri et al., 2020; Heschong et al., 2000). To achieve this goal, the performance criteria must be considered during the process of designing a classroom. Some of the most important building performance criteria are thermal comfort, annual energy requirement, and daylight availability (Konis et al., 2016).

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*Corresponding author's email: atthaillah@unimal.ac.id, Tel.: +62-85270359284
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These three aspects all influence each other. For example, in a tropical region such as Indonesia, daylight is abundantly available throughout the year. This condition may have various consequences, such as higher environmental temperature and the risk of excessive sunlight. These may contribute to more heat energy entering the building space, which means that it requires more energy to cool the internal space. Concerns about energy usage in relation to mechanical and operational costs in buildings has been previously investigated (Nwanya et al., 2016). However, to ensure that all the performance criteria are fulfilled, an integrated building design is required to obtain an optimal design solution. Some studies have attempted to optimize building design based on annual thermal comfort, energy requirements, and visual comfort with some design parameters, such as the geometric size and shape of the building and opening variations (Bakmohammadi and Noorzai, 2020; Zhu et al., 2020). Furthermore, studies have evaluated the facade shape in relation to wind infiltration, and façade retrofitting has previously been conducted (Hong et al., 2019; Darvish et al., 2020). However, building envelope materials have not been considered as a design parameter in previous studies. Clearly, building envelope materials affect thermal comfort and annual energy requirements, since they influence the heat that enters or leaves the building (Alsharif et al., 2021).

Furthermore, in Indonesia, an integrated building design optimization, particularly for a school classroom, is rather limited. Earlier studies have been limited to investigating only daylight criteria based on existing classroom design (Wibowo et al., 2017; Idrus et al., 2019; Atthaillah and Mangkuto, 2020). Studies evaluating multiple performance criteria have been conducted previously (Mangkuto et al., 2016; Primanti et al., 2020). Studies have evaluated a hypothetical office with some input parameters, including a window-to-wall ratio (WWR), orientation, and wall reflectance, a blind covering, and a blind angle to meet multiple performance criteria. However, this office had a unilateral opening on one side of the building's façade. Meanwhile, in Indonesia, most school classroom designs, particularly state schools, have a bilateral opening typology. Therefore, this study aims to optimize the design of school classrooms with bilateral opening typology design, focusing on the design of the building envelope to achieve optimal design solutions in terms of annual thermal comfort, energy requirements, and daylight availability in Lhokseumawe, Indonesia. This is considered an early study investigating an integrated building design focusing on an elementary school classroom in Indonesia. Lhokseumawe has been selected since this study has progressed from an earlier study to better understand the previous finding that suggested that shading depth is one of the strong correlation input variables for the annual daylight metric (Atthaillah et al., 2021). Thus, this study attempts to integrate more input variables and performance criteria for a more integrated design solution.

2. Methods

This paper evaluated an isolated hypothetical classroom with a size of 7 × 8 × 3.5 m^3 located in Lhokseumawe, Indonesia. The classroom dimensions were based on the school regulations in Indonesia for elementary school classrooms (Kementerian Pendidikan Nasional RI, 2007). The aperture type of the building was symmetrically bilateral with a 30% window-to-wall ratio (WWR). Furthermore, window height was set at 1.2 m, while sill height and window spacing were 1.5 m. The materials utilized for baseline construction are indicated in Table 1. The classroom was optimized based on four orientations, as shown in Figure 1. Building performance was evaluated in terms of annual daylight, thermal comfort, and energy consumption. A *Grasshopper* environment was used to simulate the building performance, with *EnergyPlus* and *OpenStudio* as its engines to evaluate energy consumption and thermal comfort, and *Radiance* was used to evaluate annual daylight metrices. All of those engines were accessed through the interface of *LadybugTools*.

Table 1 Construction materials for the baseline condition

Construction	Material	Reflectance	Transmittance
Wall	1in. Stucco - generic brick	0.5	-
Floor	6 in. Normal-weight concrete floor	0.2	-
Ceiling	6 in. Heavyweight concrete roof	0.8	-
Window	Generic clear glass	-	0.7

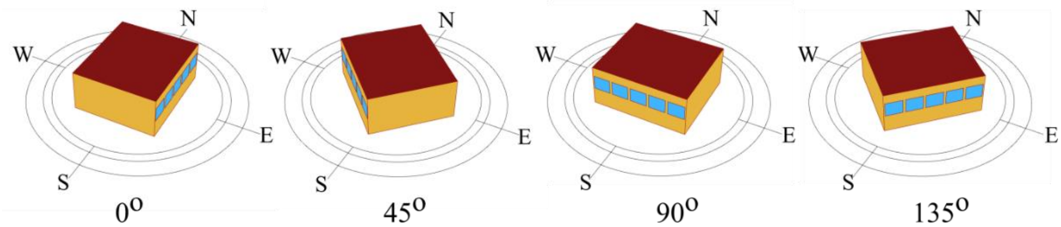


Figure 1 Illustration of the building using 0°, 45°, 90°, and 135° orientations

In this study, only cooling energy was considered when measuring building energy consumption. Heating energy was not relevant as an evaluation parameter because the building was located in the tropics region and did not require heating. Additionally, energy for electric lighting and electrical equipment was not used as a parameter because lighting strategies and equipment conditions in buildings were not adjustable or fixed.

Daylight performance was evaluated using $\text{sDA}_{300/50\%}$ and the $\text{UDI}_{100\text{-}3000\text{lx}}$ average metrics. Daylight autonomy (DA) is the percentage of daylight with an illuminance value greater than or equal to 300 lux annually from a sensor (Reinhart and Walkenhorst, 2001). In addition, spatial daylight autonomy (sDA) was used to determine the distribution of daylight in a room with an illuminance value of more than 300 lx with the coverage time of the illuminance value being at least 50% of the total measurement time, generally known as $\text{sDA}_{300/50\%}$. Useful daylight illuminance (UDI) is the percentage of illuminance measured at every measuring point in a building whose values were within a certain illuminance range within a year. UDI is applied to account for the useful illuminance level, not insufficient or excessive (Nabil and Mardaljevic, 2005), in a building. The range of illuminance values used in this study was 100-3000 lux, which is called $\text{UDI}_{100\text{-}3000\text{lx}}$ (Brembilla and Mardaljevic, 2019; Mardaljevic et al., 2011). Based on the LEED v4 standard (USGBC, 2013), it is recommended that buildings to meet specific daylight design criteria, namely $\text{sDA}_{30050\%}$ > 55%. Meanwhile, the $\text{UDI}_{100\text{-}3000\text{lx}}$ average of > 80% was first set as an appropriate daylight level in a classroom space in a Priority School Building Program (PSBP) in the UK. The $\text{UDI}_{100\text{-}3000\text{lx}}$ average is calculated using its mean illuminance values from sensors available within a space (Brembilla and Mardaljevic, 2019).

Building performance based on annual thermal comfort was represented by annual *adaptive thermal comfort neutral (ATCn),* which was assessed using the outdoor temperature based on climate data from the location of the building and the thermal comfort parameters required by the ASHRAE-55 standard (ASHRAE, 2004). In this paper, a 90% confidence level was applied when describing the range of neutral temperatures. The neutral temperature (T_n) depended on the value of the average outdoor temperature in a month ($T_{o,\,av}$), which was defined in Equation 1.

$$T_n = 17.8 + 0.31T_{o,av}\ [°\text{C}];\ \ 90\%\ confidence\ level{:}\, T_n \pm 2.5\ °\text{C} \qquad (1)$$

Therefore, the target for the design was the percentage of time in a whole year when the space condition was in the range of neutral temperatures or the ATCn maximum. If the building performance on the baseline condition does not meet the target, one needs to improve and optimize the performance. In this case, optimization was conducted by varying the parameters that affected the performance aspect(s) indicated in Table 2 (PSBP, 2013; USGBC, 2017; Brembilla and Mardaljevic, 2019). Furthermore, variations in the construction materials (walls, ceiling, floor), surface reflectance, aperture sizes, and shading construction were considered. Construction materials influenced the thermal conductivity of a building and indirectly affected the energy consumption of a building. The reflectance and the type of aperture altered the amount of daylight in a space. Shading was able to reduce overheating due to sun exposure and improved thermal comfort, while also reducing lighting energy used (Heidari et al., 2021). The considered input variations for wall, ceiling, floor, and window constructions, as well as surface and shading properties are presented in Tables 3 through 7. The consideration of the constructions is based on the possibilities of their constructability and practicality to be utilized in an Indonesian context. This study also assumes that the classroom is an elevated space or not on the ground floor. This is because most of the problematic classrooms are not located on the ground floor (Atthaillah and Bintoro, 2019a; Atthaillah and Bintoro, 2019b).

Table 2 Target parameters

Aspects	Material	Target
Annual Energy Consumption	Cooling energy consumption (kWh)	minimum
Annual Daylighting	sDA$_{300/50\%}$	>55%
	UDI$_{100\text{-}3000lx}$ (spatial average)	>80%
Annual Thermal Comfort	Generic clear glass	maximum

Source: PSBP, 2013; USGBC, 2017; Brembilla and Mardaljevic, 2019

Table 3 Wall constructions were used in this research

Construction Type	Layers			
	1	2	3	4
1	1 in stucco	Generic brick	1 in. Stucco	
2	1 in stucco	8 in. Concrete block wall	½ In. Gypsum board	
3	1 in stucco	Generic brick	Wood Frame non-res Wall Insulation-0.73	½ In. Gypsum board
4	1 in stucco	Generic brick	Wood frame wall insulation r-1.61 IP	½ In. Gypsum board
5	1 in stucco	Generic brick	Wall insulation [31]	½ In. Gypsum board

Table 4 Ceiling constructions were used in this study

Layer	Construction Type		
	Generic Interior Ceiling	Typical Insulated Exterior Mass Floor Ceiling	Typical Interior Ceiling
1	Generic light-weight concrete	4 in. Normal-weight concrete floor	100mm normal-weight concrete floor
2	Generic ceiling air gap	Typical insulation	CP02 carpet pad
3	Generic acoustic tile	Typical carpet pad	-

Table 5 Floor constructions were utilized within this study

No	Construction Type	No	Construction Type
1	Generic interior floor	4	Typical insulated carpeted 6in slab floor-r5
2	Typical insulated 6in slab floor	5	Typical uninsulated 6in slab floor
3	Typical insulated carpeted 6in slab floor		

Table 6 Surface reflectance, aperture, and shading variation

Variation	Parameter Variation	Range	Step Size
Reflectance on Construction Surfaces	Wall reflectance	0.4 – 0.7	0.1
	Ceiling reflectance	0.7 – 0.9	0.1
	Floor reflectance	0.2 – 0.5	0.1
Apertures	WWR (Window-to-wall ratio)	20% – 50%	10%
	Window's elevation	1 m – 1.5 m	0.1 m
	Transmittance	0.5-0.8	0.1
Shading	Elevation	3.3 m – 3.5 m	0.1 m
	Depth	0.5 m – 3 m	0.1 m

Table 7 Window construction variation

No	Window Construction	No	Window Construction
1	U = 0.17, SHGC = 0.31, simple glazing window	7	U = 0.20, SHGC = 0.20 simple glazing window
2	U = 0.17, SHGC = 0.32, simple glazing window	8	U = 0.20, SHGC = 0.21 simple glazing window
3	U = 0.17, SHGC = 0.36 simple glazing window	9	U = 0.20, SHGC = 0.22 simple glazing window
4	U = 0.18, SHGC = 0.22 simple glazing window	10	U = 0.23, SHGC = 0.31 simple glazing window
5	U = 0.18, SHGC = 0.24 simple glazing window	11	U = 0.23, SHGC = 0.34 simple glazing window
6	U = 0.20, SHGC = 0.19 simple glazing window		

Based on these variations, combinations that produce optimal evaluation parameters were selected, including low energy consumption, optimal natural lighting, and a high level of thermal comfort. The building performance optimization was implemented using *Galapagos* under *Grasshopper*. This optimization tool was based on *Genetic Algorithms* (GA). Optimization with *Galapagos* had a target value known as *fitness (f)*. *The fitness* was set as a function that produced building performances with low energy consumption, optimal daylight value, and a high level of thermal comfort neutral. Thus, in this study, the *fitness* function was defined as per Equation 2.

$$f = Cooling\ Energy - (ATCn + sDA_{300lx/50\%} + UDI_{100-3000lx}average) \tag{2}$$

Equation 2 was optimized for its minimum value by subtracting the cooling energy from the total sum of ATCn, $sDA_{300/50\%}$, and $UDI_{100\text{-}3000lx}$. Normalization was not performed for the output indicators, since the maximum and minimum number for cooling energy were unpredictable for the situation in this study. Therefore, the logic of the equation was constructed based on the condition if the ATCn, $sDA_{300/50\%}$, and $UDI_{100\text{-}3000lx}$ were maximized regardless of their units, and the total cooling energy was deducted. Therefore, based on the optimization, results that had a maximum combination of the ATCn, $sDA_{300/50\%}$, and $UDI_{100\text{-}3000lx}$ were the optimal solutions.

3. Results and Discussion

Based on the simulation of the baseline building conditions, the obtained performance indicators of the classroom are indicated in Table 8. The results reveal the highest annual energy requirements; they suggest that thermal comfort and natural lighting performance have the lowest value at a 90° orientation. This demonstrates that sunlight is dominant in the direction of the opening at a 90° orientation (openings facing north and south). In addition, in all orientations, the annual energy demand for the cooling load is relatively high, at around 40,000 kWh per year, the percentage of ATCn is around 67%, and the UDI$_{100-3000lx}$ average value is around 60%. This value is still below the design target, which is a UDI$_{100-3000lx}$ average of more than 80%. Therefore, the optimization of the building design aims to reduce the value of the cooling load and increase the value of the ATCn and average UDI$_{100-3000lx}$.

Table 8 Building performance with baseline conditions for each building orientation

Parameters		Building Orientations			
		0°	45°	90°	135°
Annual Energy Need	Cooling [kWh]	40,413	40,640	40,861	40,261
Thermal Comfort	ATCn [%]	67.89	67.68	67.60	67.68
Daylight Metrics	sDA$_{300/50\%}$ [%]	100	100	100	100
	UDI$_{100-3000lx}$ average [%]	66.98	62.44	57.33	60.95

Table 9 Optimum building design parameters at orientation 0°, 45°, 90°, 135°

Input Parameters	Building Orientations			
	0°	45°	90°	135°
Shading elevation (m)	3.3	3.3	3.3	3.4
Shading depth (m)	3	3	3	3
WWR (%)	20	20	20	20
Aperture elevation (m)	1.5	1.5	1.5	1.5
Wall surface reflectance	0.4	0.6	0.6	0.4
Ceiling surface reflectance	0.7	0.8	0.7	0.7
Window transmittance	0.5	0.6	0.6	0.6
Floor surface reflectance	0.2	0.2	0.2	0.2
Wall construction	Wall construction type 5	Wall construction type 5	Wall construction type 3	Wall construction type 5
Ceiling construction	Generic interior ceiling	Generic interior ceiling	Generic interior ceiling	Generic interior ceiling
Window construction	U=0.20, SHGC = 0.19 simple glazing window	U=0.20, SHGC = 0.19 simple glazing window	U=0.20, SHGC = 0.19 simple glazing window	U=0.20, SHGC = 0.19 simple glazing window
Floor construction	Generic interior floor	Generic interior floor	Generic interior floor	Generic interior floor

Table 10 Comparison of building performance at the baseline and optimal conditions at a building orientation of 0° and 45°

Output Parameters		Building Orientations					
		0°			45°		
		Baseline	Optimum	Δ	Baseline	Optimum	Δ
Annual Energy Need	Cooling (kWh)	40,413	**30,873**	**-23.6%**	40,677	**30,819**	**-24.2%**
Thermal Comfort	ATCn	67.9%	**93.8%**	**+38.2%**	67.7%	**93.9%**	**+38.7%**
Daylight Metrics	sDA$_{300lx/50\%}$	100%	100%	0%	100%	100%	0%
	UDI$_{100-3000lx}$ average	67.0%	**96.9%**	**+44.7%**	62.4%	**98.5%**	**+57.7%**

Subsequently, the optimization of the building design was ensured by changing the input parameters to achieve the desired building performance. The input parameters encompass the walls, ceilings, floors, windows, and shading devices. The desired building performance is based on the fitness function, which involves several building measures, such as annual energy requirements, thermal comfort, and daylight availability. The optimal building design with building orientations of 0°, 45°, 90°, and 135° are shown in Table 9.

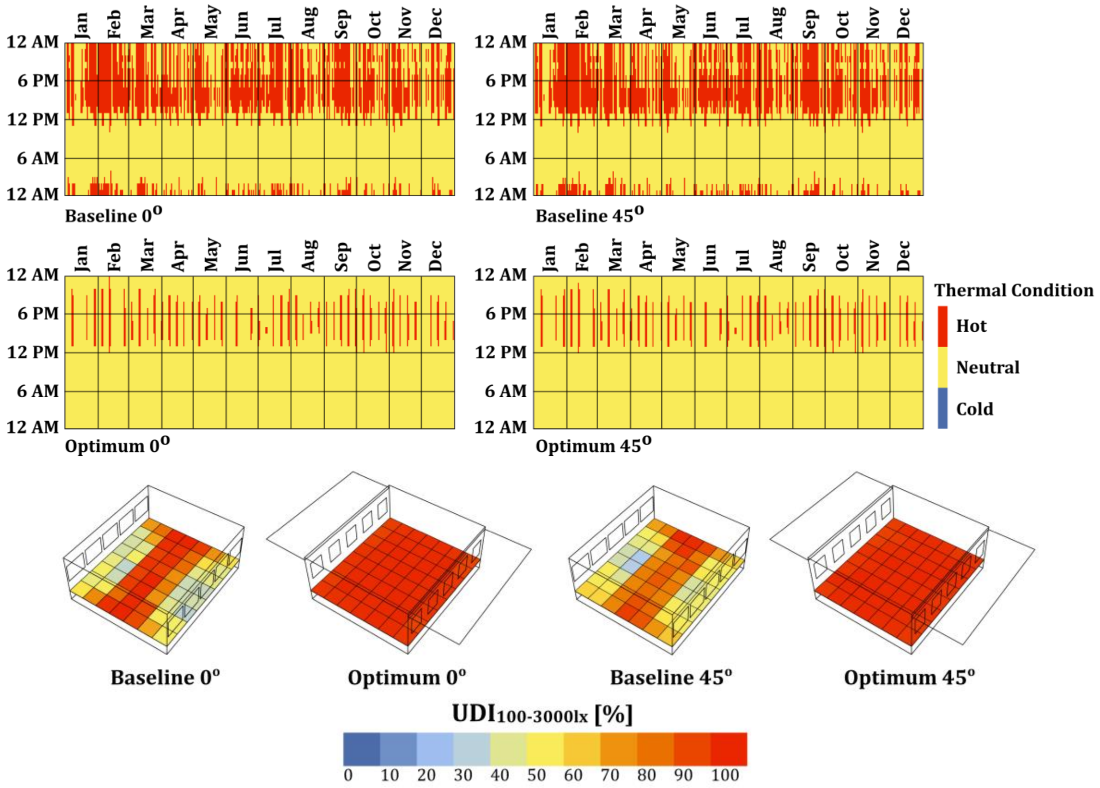
Table 9 indicates the design parameters that affect the opening; the building design results are similar for each orientation, namely WWR = 20% and aperture elevation = 1.5 m. For design parameters that affect the shade, the building orientations of 0°, 45°, and 90° have an equal shade elevation at 3.3 m height. Meanwhile, at orientation 135°, it is 0.1 m higher (i.e. 3.4 m). The optimal shading depth obtained at each orientation is 3 m. The ceiling construction, floor construction, and optimal window material achieved at every orientation have a similar value. In contrast, the wall construction of some orientations varied. The optimum wall construction at 0°, 45°, and 135° orientations is wall construction type 5, while the optimum wall construction at 90° orientation is wall construction type 3.

Table 11 Comparison of building performance in the baseline and optimal conditions at building orientation 90° and 135°

Output Parameters		Building Orientations					
		90°			135°		
		Baseline	Optimum	Δ	Baseline	Optimum	Δ
Annual Energy Need	Cooling (kWh)	40,861	**31,186**	**-23.7%**	40,640	**30,816**	**-24.2%**
Thermal Comfort	ATCn	67.6%	**93.5%**	**+38.3%**	67.7%	**93.9%**	**+38.8%**
Daylight Metrics	$sDA_{300lx/50\%}$	100%	100%	0%	100%	100%	0%
	$UDI_{100-3000lx}$ average	57.3%	**98.2%**	**+71.3%**	62.4%	**97.8%**	**+56.6%**

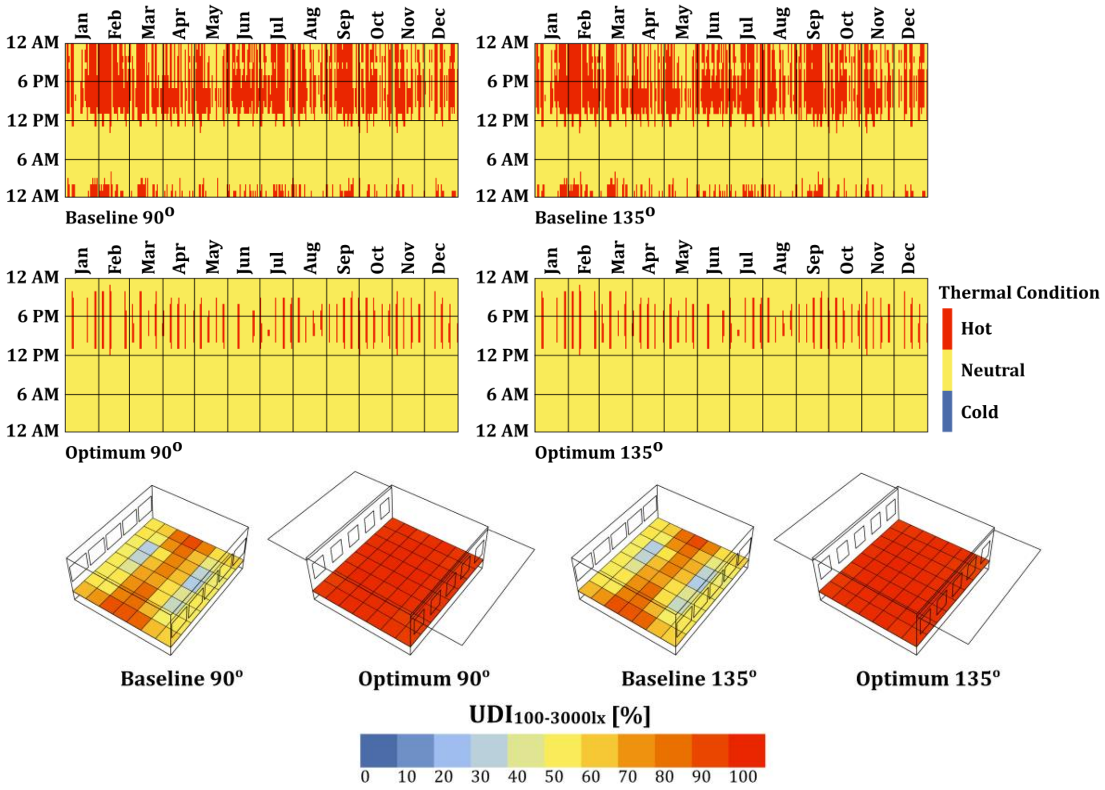
In addition, the lowest cooling energy consumption was found at a 135° orientation (30,816 kWh). The low energy consumption of the classroom contributed to the highest adaptive comfort level (93.9%) at this orientation. However, the variations relative to other orientations are insignificant. The $UDI_{100-3000lx}$ average has the highest value at a 45° orientation, with omittable variation compared to the other orientations. Furthermore, the comparison between building performance with the baseline design and optimal building design based on annual thermal comfort, energy requirements, and daylight availability are presented in Tables 10 and 11 and illustrated in Figures 2 and 3. The tables indicate that the optimized combinations of input parameters can reduce the cooling energy consumption from 23.6% to 30,873 kWh (building orientation = 0°), 24.2% to 30,818.8 kWh (building orientation = 45°), 23.7% to 31,186.3 kWh (building orientation = 90°), and 24.2% to 30,816.3 kWh (building orientation = 135°), compared to the baseline design. This occurs due to the reduced thermal energy from the wall infiltration and glass radiation, which results in a significant increase in the thermal comfort levels as follows: orientation 0°: from 67.9% in the baseline to 93.8%, orientation 45°: from 67.7% in the baseline condition to 93.9%, orientation 90°: from 67.6 % in baseline conditions to 93.5%, and orientation 135°: from 67.7% in baseline conditions to 93.9%.

Figures 2 and 3 present thermal graphs illustrating the decrease in thermal energy inside the building space, which occurred predominantly at 12:00 PM – 12:00 AM. In addition, the $sDA_{300/50\%}$ values remained 100% for all building orientations.



(a) (b)

Figure 2 Comparison of building performance in the baseline and optimum conditions at building orientation 0° (a) and 45° (b)



(a) (b)

Figure 3 Comparison of building performance in the baseline and optimum conditions at building orientation 90° (a) and 135° (b)

Meanwhile, $UDI_{100\text{-}3000lx}$ average values significantly increased in each building orientation, as follows: orientation 0°: from 44.7% to 96.9%, orientation 45°: from 57.7% to 98.5%, orientation 90°: from 71.3% to 98.2%, orientation 135°: from 56.6% to 97.8%. The increases of $UDI_{100\text{-}3000lx}$ average values occurred due to the reduction of excessive sunlight illuminance at the area close to the window on both sides. The over-lit area in the building space was reduced due to the existence of shading devices that prevented direct sunlight (Heidari et al., 2021).

It was found that the most optimal design solution for the symmetrical bilateral opening typology can utilize similar values and construction types (Table 9) for all orientations investigated within this study. Meanwhile, input variable variations are mostly related to surface material properties, such as window transmittance and wall and ceiling reflectance. For the symmetrical bilateral opening typology, a longer shading depth with a combination of relatively lower shading elevation is recommended to obtain the optimal design solution for all orientations. Additionally, a relatively higher window elevation is required to comply with energy, thermal, and daylight performance criteria. Further investigations on asymmetrical opening typology are nevertheless still required to better understand these phenomena in such classrooms.

4. Conclusions

This paper has integrated several elements of evaluating and optimizing building performance. The optimization has yielded a hypothetical sustainable classroom, which is thermally comfortable, has good annual daylight availability, and consumes a low amount of electrical energy annually. The classroom has a symmetrical bilateral opening and shading typology and is located in Lhokseumawe, Indonesia. In the baseline condition, the building space is dominated by excessive daylight with high illuminance. This is indicated by the high $sDA_{300/50\%}$ value of 100% and a low $UDI_{100\text{-}3000lx}$ average value of around 50-60%. Meanwhile, the adaptive thermal comfort percentage is around 67%, and the cooling energy consumption is around 40,000 kWh per annum. Furthermore, after optimization, the building space is now dominated by useful daylight, indicated by the high $UDI_{100\text{-}3000lx}$ average value of around 98% and the high $sDA_{300/50\%}$ value of 100%. Despite the high illuminance in the classroom, the adaptive thermal comfort percentage in the internal space has increased to around 98%. The cooling energy consumption also decreased by about 23-24% compared to the baseline condition, to around 30,000 kWh.

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