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STUDY OF HORIZONTAL LIGHT PIPE WITH DYNAMIC REFLECTOR IN THE TROPICS

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ABSTRACT

Horizontal light pipe (HLP) is a sustainable strategy for improving daylighting quality in buildings. The reflector is one of the HLP elements that collect and direct the incoming light in the pipe. Several reflector studies of HLP systems have been carried out in the last three decades under specific sunlight conditions at certain altitudes and azimuths or static conditions. This study proposes a dynamic reflector model in response to the movement of the sun angle. This study aimed to examine the impact of the dynamic reflector tilt angle on improving the quality of light by adapting the sun angle. The method used is an experimental simulation using IESVE software. This research is located in Surabaya, with a tropics climate. The results showed that modifying the reflector to be dynamic could increase the illuminance levels up to 29.9%, daylight factor values up to 29.2%, and uniformity ratio values up to 33.3%.

Keywords: Horizontal Light Pipe; reflector tilt angle; daylight quality.

INTRODUCTION

Global warming is caused by continuous development regardless of the energy consumed and the amount of carbon footprint of the total CO_2 emissions caused. Lighting systems in buildings consume the second most energy (35%) after cooling systems (40%) (Brasington, 2019). Sustainable architecture is a strategy for adequate environmental protection, the wise use of natural resources, and most importantly, for a better quality of life for all people now and in the future. One sustainable strategy is implementing an innovative daylight system (IDS) to improve the daylight quality in buildings (Wong, 2017). The use of natural lighting in tropical climates buildings can save energy and provide physiological and occupant health (Sassi, 2006). The design of the building in a suitable tropical climate provides the potential to take advantage of natural lighting. Illumination levels in tropical climates can reach more than 60,000 Lux in cloudy sky conditions and more than 80,000 Lux in clear sky conditions (Zain-Ahmed et al., 2002).

The deep-plan design in office buildings increases to take advantage of the leased floor area. The design impacts natural lighting not available in areas far from the side windows. Increasing the window size to increase natural light is ineffective in tropical climates (Beltran et al., 1997; Ruck & Aschehoug, 2000). Therefore, a core daylighting system is needed for lighting systems in areas far from side windows (Linhart et al., 2010). The HLP system can distribute natural lighting with a depth of field of more than 10m through side lighting (Beltran et al., 1997). Aperture, pipe, and opening distribution are the main elements of an HLP system. The reflector is an important element in the aperture of the HLP system to direct the light inside the pipe. Previous research has discussed the development of the HLP reflector model to obtain optimal natural lighting. Several previous journals showed the importance of applying reflectors in HLP systems by examining the effect of modifying reflectors to maximize light transmission. The study (Hansen & Edmonds, 2003) tested the application of a laser-cut panel (LCP) as a reflector and collector of sunlight in a light pipe system. This study describes LCP as an important reflector to increase light transmission because it serves to direct sunlight more axially on the pipe. In addition, the LCP as a reflector serves to reduce reflections and increase the uniformity of light in space. This study concludes that modifying the reflector on the light pipe system affects an adequate spatial light distribution.

The second study (Obradovic et al., 2021) examines custom-made reflectors that affect the visual perception of office building users. The research was conducted by collecting a survey of building occupants' impressions of a room without the HLP system and a space using a custom-made HLP reflector system. The survey results show that residents perception in a room with a custom-made HLP system reflector. The light level is lower but comfortable to carry out activities, and the eyes are more relaxed than in a room without HLP. This study concludes that office occupants prefer a space with a custom-made reflector on the HLP system because the impression of the space is more positive and pleasant. The application of a mirror reflector on the HLP has provided clearer visuals, sharper light variations, and more sparkling light. The third study (Obradovic & Matusiak, 2021) tested the configuration of the laser cut panel at the HLP aperture as a reflector to increase the transmission of HLP light. The results show that the application of LCP as a reflector can redirect the sun's negative angle of incidence, becoming more axial along the pipe. Type T LCP and type R LCP can increase visual comfort for building occupants. The difference between the performance of the two systems is that the type T LCP works better in cloudy skies, and the R type LCP works better in clear sky conditions.

In the last three decades, several previous studies have carried out precise calculation methods to increase pipe light transmission. However, some of these studies ended by considering static conditions (Canziani et al., 2004; Obradovic & Matusiak, 2021). The study (Canziani et al., 2004) showed that by using a static reflector, in June and December, the condition of the sun's trajectory was north and south of the equator, the illuminance level decreased by 12% (June) and 5% (December). The daylight factor value in June decreased by 11%, and in December decreased by 6%. Therefore, a dynamic reflector system is needed in HLP systems (Canziani et al., 2004).

In response to current climatic conditions and office space design by developing previous studies on HLP systems, there is an opportunity to investigate the angle of inclination of the reflector of the HLP system by adjusting the angle of incidence of the sun over a period of one year. Previous research proposed a static HLP system reflector. So different from previous research, this study proposes a dynamic reflector model with a tilt angle that adjusts the angle of incidence of the sun. The case study for this research is Praxis Tower Surabaya room type 3A-05, with the direction facing the HLP aperture northwest. This study focuses on the design of the dynamic reflector model. So the purpose of this study was to examine the effect of the tilt angle of the dynamic reflector on the HLP system on improving the quality of natural lighting in the room through the values of illuminance levels, daylight factor, and uniformity ratio. This research is located in Surabaya, Indonesia, in a tropical climate.

THEORETICAL FRAMEWORK

Research simulations were carried out on March 21, June 21, September 21, and December 21 as one-year measurements. March 21 and September 21 are equinox conditions, which are conditions where the sun's path is directly above the equator. Meanwhile, June 21 and December 21 are solstice conditions, namely the condition of the sun's trajectory to be most north and south of the equator (Sinha, 2021). The following table shows the sun's position on March 21, June 21, September 21, and December 21.

Table 1. The sun’s position during working hours

Time	Altitude (˚)	Azimuth (˚)
March 21		
10:00	64.84	73.56
12:00	80.38	321.78
15:00	38.64	276.32
17:00	9.02	271.56
June 21		
10:00	52.13	35.23
12:00	58.49	347.15
15:00	30.46	302.68
17:00	4.32	294.28
September 21		
10:00	68.03	69.72
12:00	77.71	309.50
15:00	35.14	275.85
17:00	5.56	271.24
December 21		
10:00	63.58	130.13
12:00	72.01	205.13
15:00	36.56	246.13
17:00	9.19	247.31

(Source: https://www.suncalc.org/#/7.2631,112.7313,12/2021.12.21/18:00/1/3)

Visual function parameters are used to determine whether certain lighting conditions allow vision or visibility and affect the physiology of the eye. The amount of light adequate determines good visibility for visuals and the uniformity of light (Ruck & Aschehoug, 2000). Illuminance is a metric used to measure light intensity. Illuminance is measured in footcandles or lux, the amount of light falling on a surface. Lighting professionals use a light measuring device, namely an illuminance meter or lux meter, to measure the amount of light in space on a particular work surface (Preto & Gomes, 2018). The illuminance value can be calculated by the following formula (Kristanto, 2021):

$$E = (L \times n) \times CU \times LLF / A \quad (1)$$

Where:
E = illuminance (Lux)
L = lumen
N = number of lamps
CU = coefficient of utilization (0,5)
LLF = light loss factor
A = area

Daylight factor (DF) is the ratio of indoor to outdoor horizontal illumination with overcast conditions and is expressed as a percentage. The daylight factor gives the minimum standard of lighting in a room. Two types of DF can be calculated, namely at a particular position (Point DF) and DF above a specific floor area (DF_{ave}).

$$DF = \frac{Indoor\ illuminance\ from\ daylight}{Horizontal\ unobstructed\ outdoor\ illuminance}\ x\ 100\% \quad (2)$$

The average daylight factor (DF_{ave}) is the ratio of the average interior to the horizontal illuminance of the exterior under overcast sky conditions. It can represent the arithmetic mean of DF obtained for the entire room. The minimum DF_{ave} value for interior spaces is less than 2% for artificial lighting to 5% for the use of natural lighting during the day (Wong, 2017). The uniformity ratio describes lighting quality in the area where residents perform visual tasks. The uniformity ratio is the balance between the lighting in the work area and the surrounding zone. Illumination uniformity is expressed by the ratio of the minimum illumination to the average illumination of a surface(Galatioto & Beccali, 2016).

$$UR = \frac{\mathrm{Emin}}{\mathrm{Eavg}} \quad (3)$$

Where:
UR = uniformity ratio
Emin = minimum illuminance
Eavg = average illuminance

BREEAM recommends a uniformity ratio in a minimum room ratio of 0.4 to a table height of 0.7m (Vaisi & Kharvari, 2019). A higher level of uniformity will provide better visuals for occupants. However, there are no specific guidelines regarding the uniformmity ratio for all room facilities. Most previous studies analyzed the uniformity of space for office building facilities (Alrubaih et al., 2013)

This study uses the HLP model (Beltran et al., 1997), namely Light Pipe A, as the basic model because it can be modified on the reflector to become a dynamic reflector.

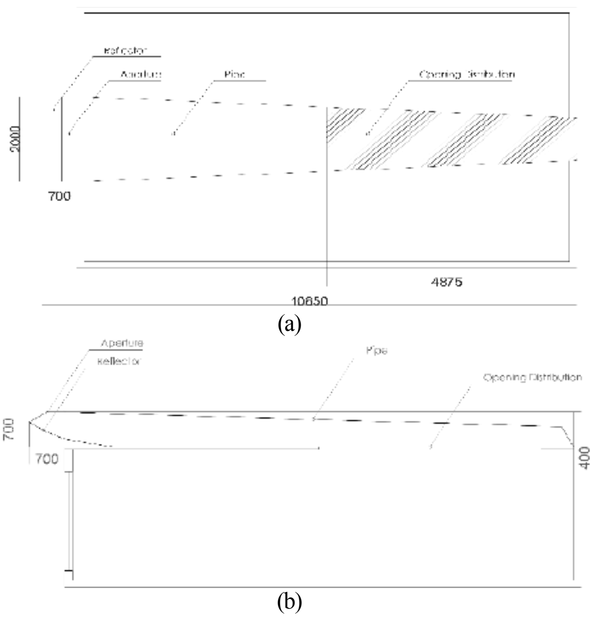


Fig. 1. (a) Room plan with Light Pipe A system (b) Room section with Light Pipe A system

Light Pipe A uses one central reflector at the aperture. The height of the pipe narrows towards the back of the pipe, with a height of 0.7m at the front and 0.4m at the back of the pipe. The shape of the pipe plan is trapezoidal with a cone at the back to focus light into the pipe. For pipe material, use a material with a reflectance value of 99%.

Table 2. Materials used in office space and HLP systems

Element	Reflec-tance (%)	Specularity Value	Roughness Value	Type	Visible Transmit-tance
Wall	70	0.03	0.03	Plastic	
Floor	20	0.03	0.2	Plastic	
Ceiling	80	0.03	0.03	Plastic	
Light Pipe	99	0.9	0.03	Metal	
Glazing Window					0.75
Glazing Light Pipe					0.88

(Source: (Heng et al., 2020))

The research was conducted in office buildings in Surabaya, which have a depth of more than 9 m, so it is necessary to use electrical lighting because they do not get enough natural lighting. The case study selected in this research is Praxis Tower Surabaya. The office space as a case study is 3A-05 with a side window orientation in the northwest.

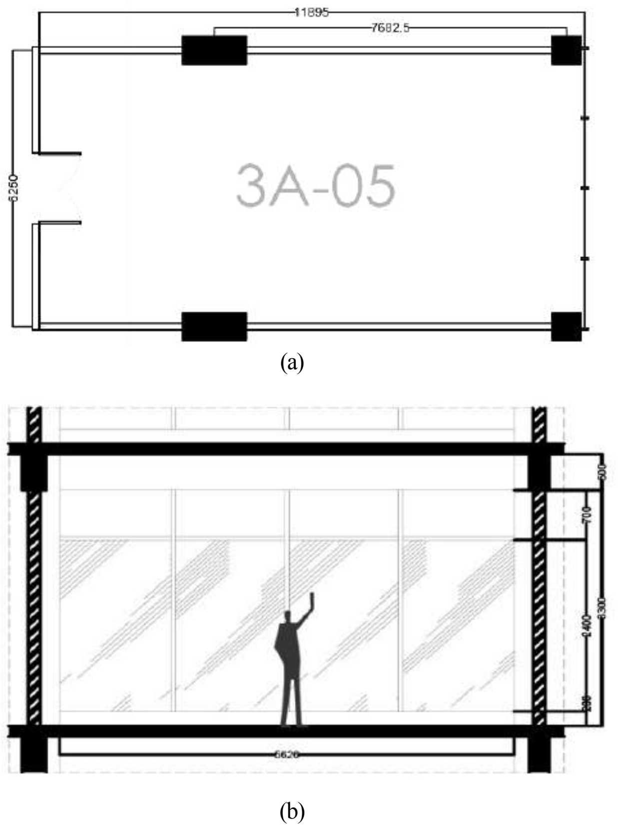


Fig. 2. (a) Room office plan as study case (b) Room section as study case

METHODOLOGY

The method used in this research is an experiment using software simulation. The simulation was carried out by comparing the condition of the office space without HLP (base case), the condition of the office space with an HLP static reflector (case 1), and the condition of the office space with an HLP dynamic reflector (case 2). The reference to the primary HLP model case 1 and case 2 is the HLP model (Beltran et al., 1997) Light Pipe A. By looking at the sun's angle data, the first thing to do is calculate the tilt angle of the reflector. After getting the reflector tilt angle, the design and simulation will be carried out on the IESVE software. The sky condition used to determine the illuminance levels and uniformity ratio values is a clear sky. The sky condition used to determine the daylight factor value, according to (chapter 2), is overcast. Taking the value is at a working plan height of 0.8.

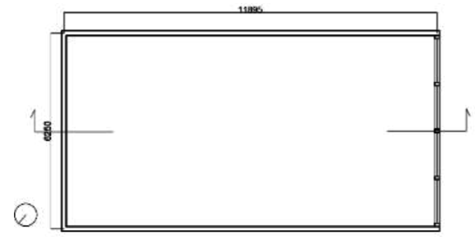
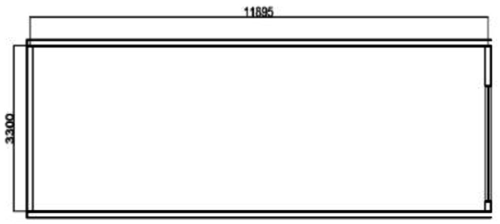
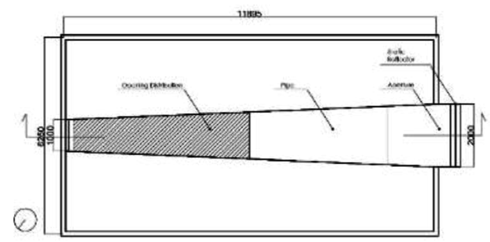
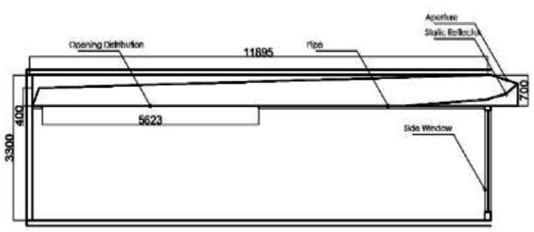
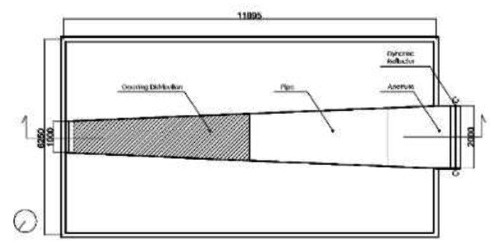
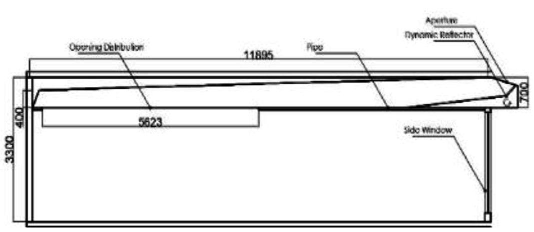
The simulation software used after designing the model is Radiance IES (daylighting and electrical lighting simulation). Studies (Oleiwi et al., 2019) prove that the difference in the results of direct measurements using the IES-VE software is acceptable, which is around 10-20%. IESVE was chosen as a tool because it meets international standards. IESVE has been validated under ASHRAE standard 140 and published for all versions of ASHRAE standard 140; 2001, 2004, 2007, and 2014. IESVE software complies with the requirements of the ISO 52000 standard.

RESULTS AND DISCUSSION

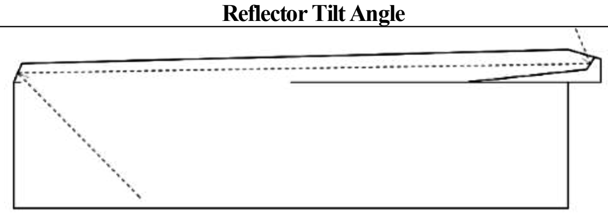
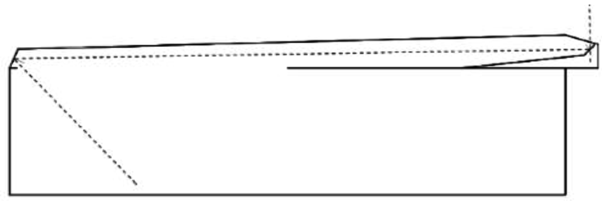
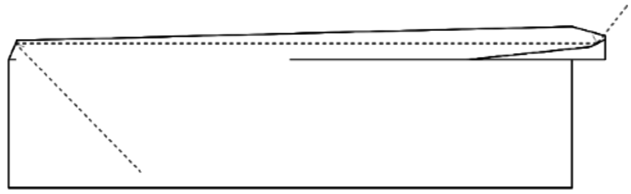
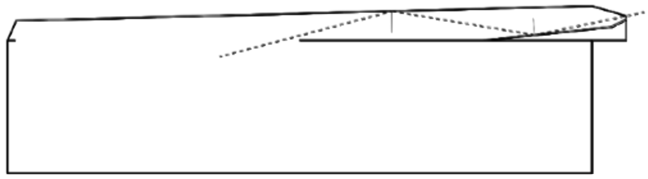
The sun angle data (chapter 2) determines the reflector tilt angle. The reflector tilt angle is to direct sunlight that enters the pipe, then reflected towards the back of the pipe, and distributed into the room area. The sunlight is directed directly at the back of the pipe to minimize the loss of light transmission value due to reflections. The following table shows the reflector tilt angle data.

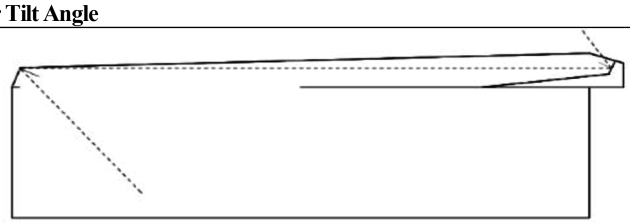
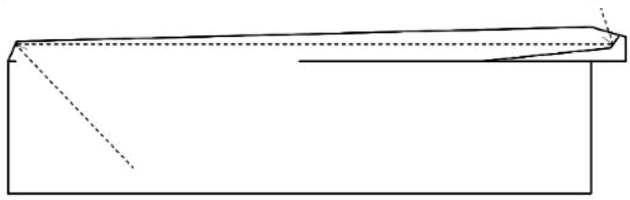
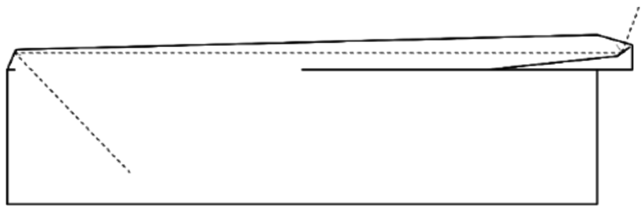
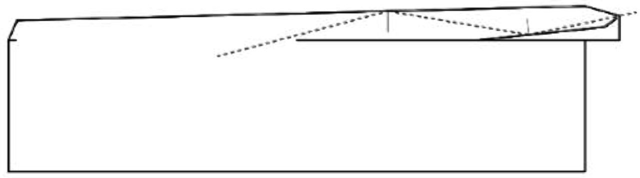
The reflector tilt angle data is used to design the HLP model as case 2, with a dynamic reflector in the IESVE software. The material for the light pipe has a reflectance value of 99%. HLP glass material has a visible transmittance value of 0.88 to support light transmission in the pipe. Simulations were carried out in the base case, case 1, and case 2. The sky condition for obtaining the illuminance levels was clear sky, while the sky condition for obtaining the daylight factor value was an overcast sky. Measurements were made at a working plane height of 0.80m.

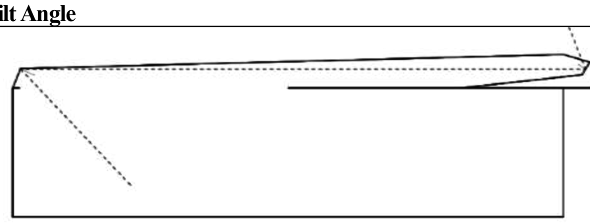
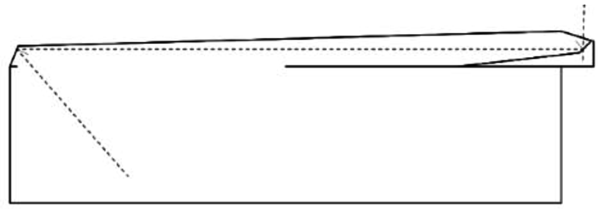
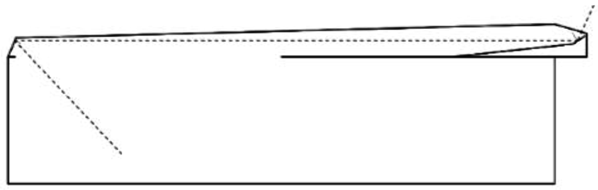
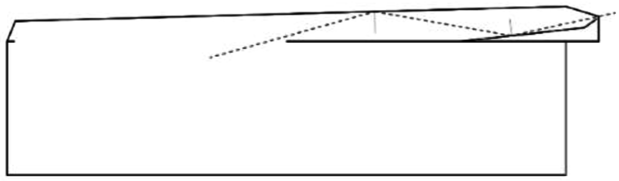
Table 3. The configuration base case, case 1, and case 2

	Plan	Section
Base Case		
Case 1		
Case 2		

Tabel 4. The tilt angle of the reflector based on the sun's position

March 21	
Time	**Reflector Tilt Angle**
10.00 Reflector tilt angle (57^o)	
12.00 Reflector tilt angle (45^o)	
15.00 Reflector tilt angle (27^o)	
17.00 Reflector tilt angle (27^o)	

June 21	
Time	**Reflector Tilt Angle**
10.00 Reflector tilt angle (63^o)	
12.00 Reflector tilt angle (54^o)	
15.00 Reflector tilt angle (34^o)	
17.00 Reflector tilt angle (34^o)	

September 21	
Time	**Reflector Tilt Angle**
10.00 Reflector tilt angle (57^o)	
12.00 Reflector tilt angle (44^o)	
15.00 Reflector tilt angle (33^o)	
17.00 Reflector tilt angle (33^o)	

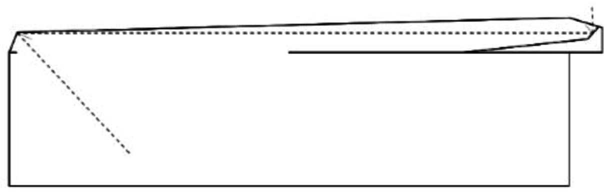
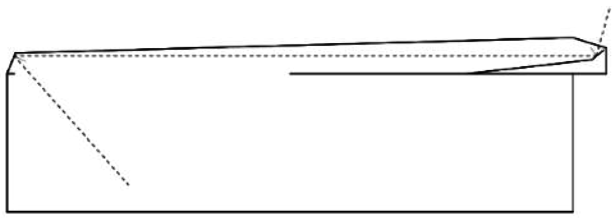
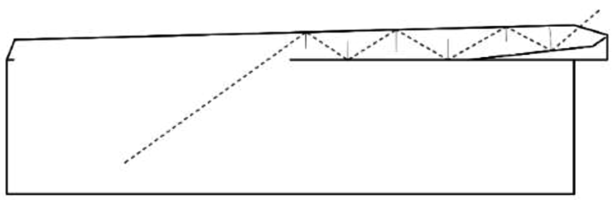
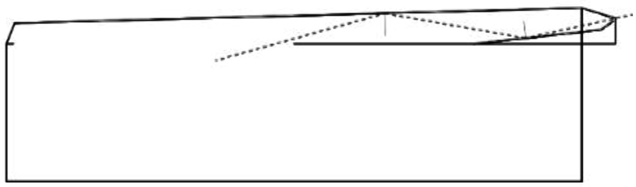
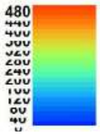
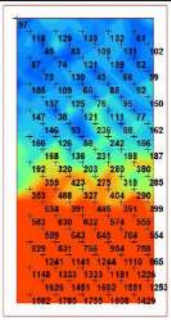
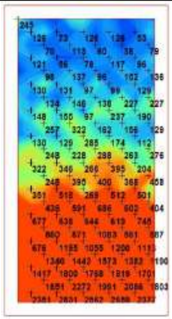
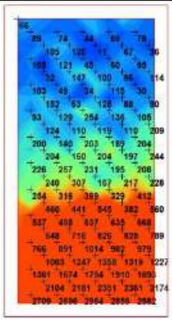
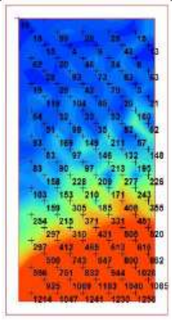
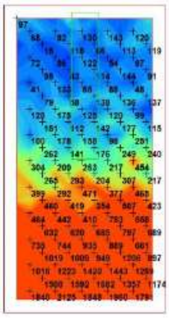
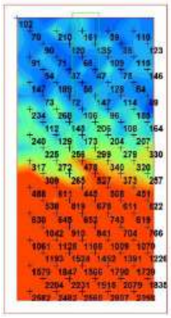
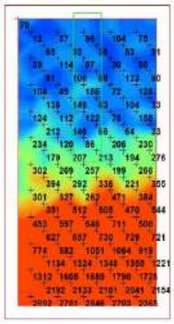
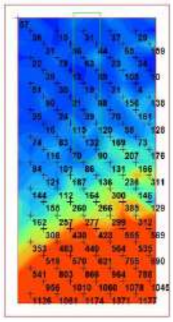
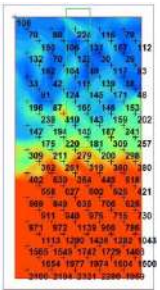
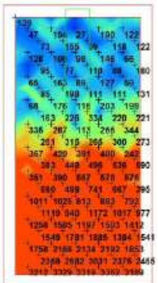
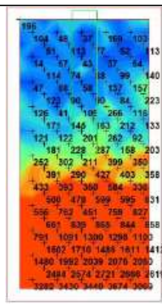
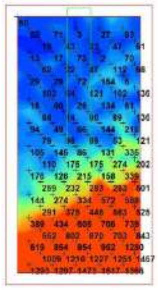
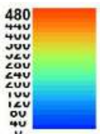
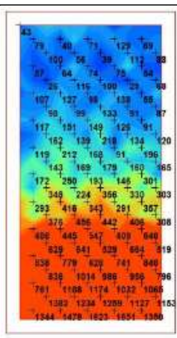
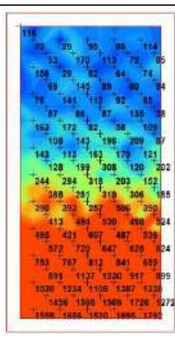
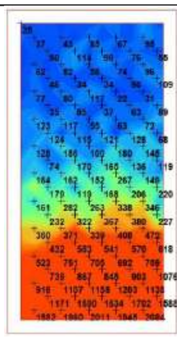
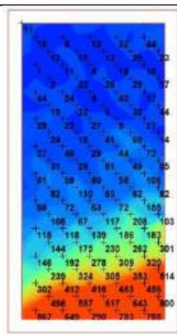
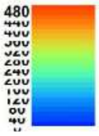
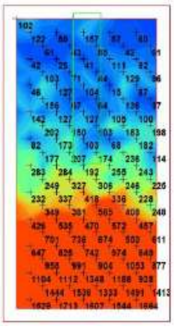
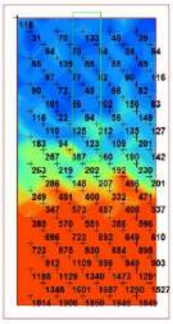
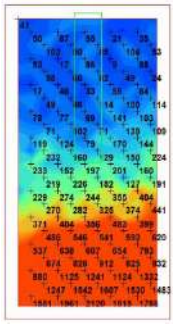
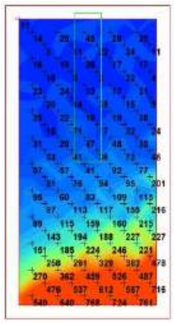
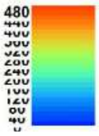
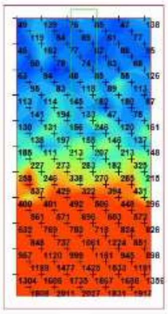
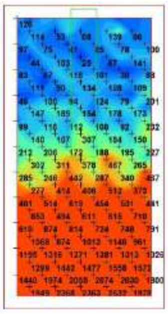
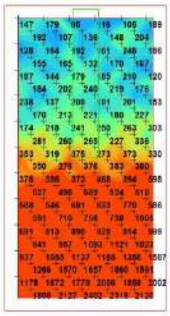
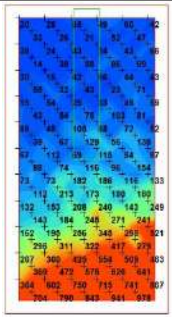
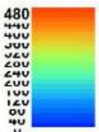
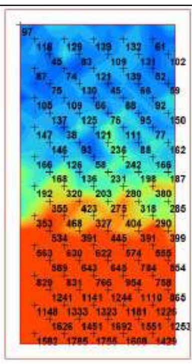
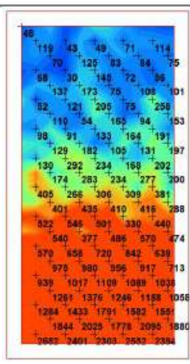
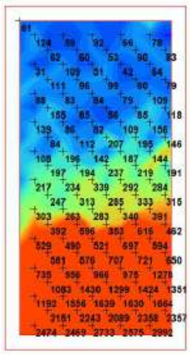
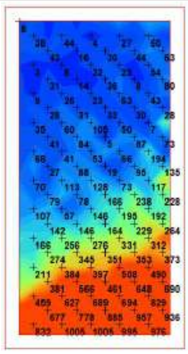
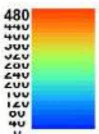
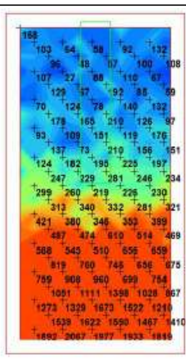
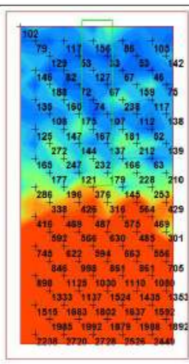
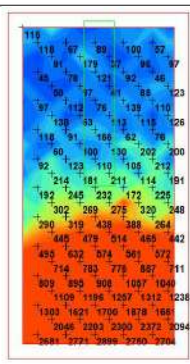
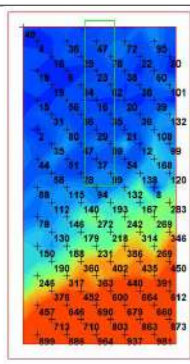
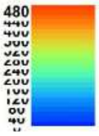
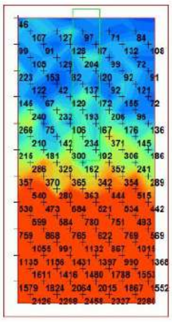
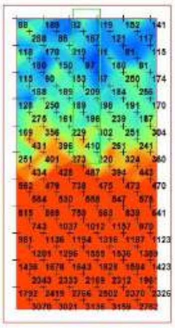
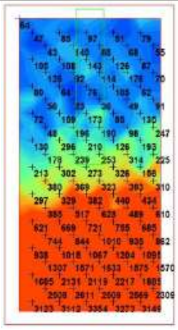
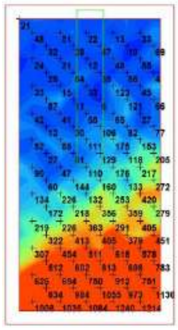
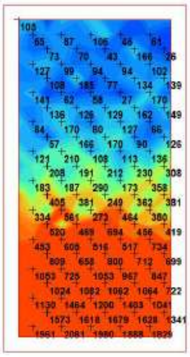
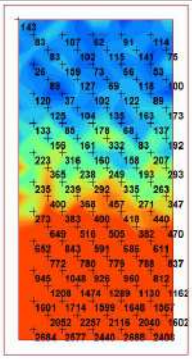
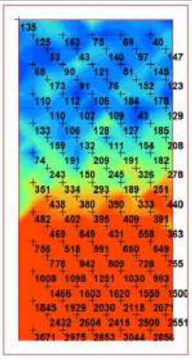
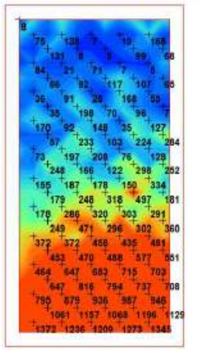
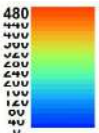
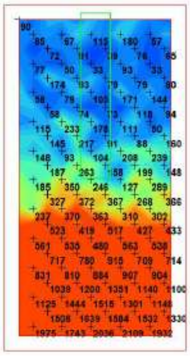
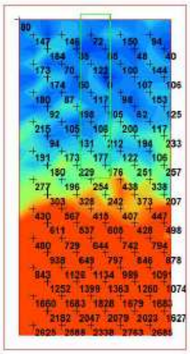
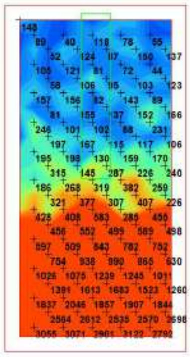
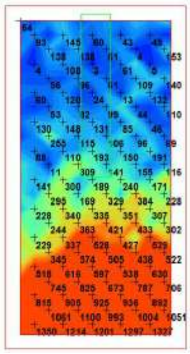
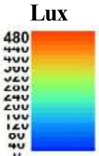
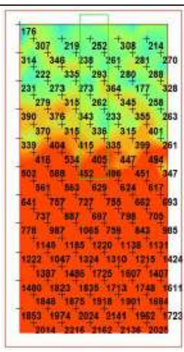
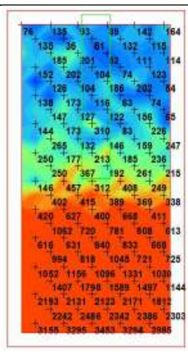
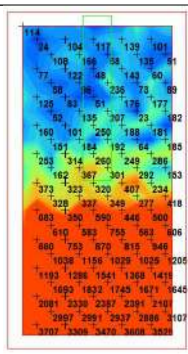
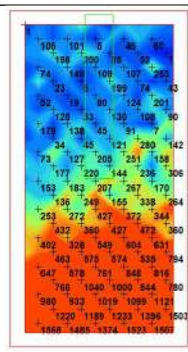
December 21	
Time	**Reflector Tilt Angle**
10.00 Reflector tilt angle (47^o)	
12.00 Reflector tilt angle (37^o)	
15.00 Reflector tilt angle (33^o)	
17.00 Reflector tilt angle (33^o)	

Table 5. Simulation results

Results		**Time**			
		March 21			
		10.00	**12.00**	**15.00**	**17.00**
Base Case	**Lux** 	 Av. 481.42	 Av. 646.09	 Av. 602.69	 Av. 308.08
	DF	2.14	2.26	2.27	2.27
	UR	0.104	0.084	0.058	0.063
Case 1 Static Reflector	**Lux** 	 Av. 490.64	 Av. 646.06	 Av. 594.25	 Av. 298.93
	DF	2.14	2.13	2.17	2.12
	UR	0.127	0.89	0.070	0.068
Case 2 Dynamic Reflector	**Lux** 	 Av. 594.08	 Av. 785.41	 Av. 716.73	 Av. 347.23
	DF	2.46	2.45	2.47	2.42
	UR	0.129	0.092	0.072	0.078
Results		**Time**			
		June 21			
		10.00	**12.00**	**15.00**	**17.00**
Base Case	**Lux** 	 Av. 431.77	 Av. 471.28	 Av. 419.22	 Av. 160.56
	DF	2.28	2.29	2.28	2.32
	UR	0.117	0.103	0.048	0.050

Case 1 Static Reflector	**Lux** 	 Av. 445.15	 Av. 481.58	 Av. 422.06	 Av. 154.55
	DF	2.15	2.14	2.16	2.18
	UR	0.119	0.103	0.068	0.072
Case 2 Dynamic Reflector	**Lux** 	 Av. 494.79	 Av. 576.43	 Av. 620.06	 Av. 208.65
	DF	2.47	2.56	2.86	2.93
	UR	0.130	0.114	0.114	0.113

Results		**Results**			
		September 21			
		10.00	**12.00**	**15.00**	**17.00**
Base Case	**Lux** 	 Av. 481.42	 Av. 611.88	 Av. 589.93	 Av. 244.17
	DF	2.28	2.28	2.29	2.31
	UR	0.088	0.062	0.066	0.076
Case 1 Static Reflector	**Lux** 	 Av. 508.60	 Av. 614.29	 Av. 591.16	 Av. 242.23
	DF	2.14	2.16	2.15	2.14
	UR	0.126	0.093	0.066	0.085

Case 2 Dynamic Reflector	**Lux** 	 Av. 595.95	 Av. 775.19	 Av. 692.61	 Av. 288.85
	DF	2.54	3.45	2.56	2.55
	UR	0.126	0.102	0.073	0.088
Results		**Time**			
		December 21			
		10.00	**12.00**	**15.00**	**17.00**
Base Case	**Lux** 	 Av. 494.44	 Av. 614.45	 Av. 699.36	 Av. 366.75
	DF	2.28	2.30	2.30	2.31
	UR	0.094	0.075	0.061	0.056
Case 1 Static Reflector	**Lux** 	 Av. 506.08	 Av. 608.62	 Av. 691.88	 Av. 358.27
	DF	2.16	2.17	2.15	2.13
	UR	0.108	0.076	0.072	0.086
Case 2 Dynamic Reflector	**Lux** 	 Av. 849.45	 Av. 700.90	 Av. 808.95	 Av. 428.31
	DF	2.94	2.47	2.57	2.57
	UR	0.169	0.078	0.079	0.095

The simulation results table is then graphed to determine the increased illuminance levels, daylight factor, and uniformity ratio value. The following is a graphic image for the average increase in the values of illuminance levels, daylight factor, and uniformity ratio.

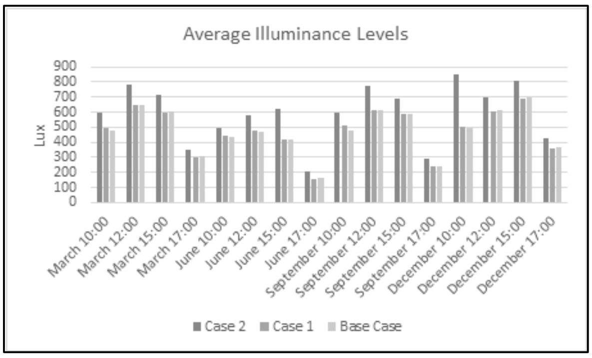


Fig. 3. Average illuminance levels Case 2, Case 1, and Base Case

The average increase in illuminance levels in March between case 2 (dynamic reflector) and case 1 (static reflector) was 19.9%, while between case 2 (dynamic reflector) and the base case was 19.1%. The average increase in illuminance levels in June between case 2 (dynamic reflector) and case 1 (static reflector) was 28.2%, while between case 2 (dynamic reflector) and the base case was 28.7%. The average increase in illuminance levels in September between case 2 (dynamic reflector) and case 1 (static reflector) was 20%, while that between case 2 (dynamic reflector) and the base case was 21.5%. The average increase in illuminance levels in December between case 2 (dynamic reflector) and case 1 (static reflector) was 29.9%, while between case 2 (dynamic reflector) and the base case was 29.6%.

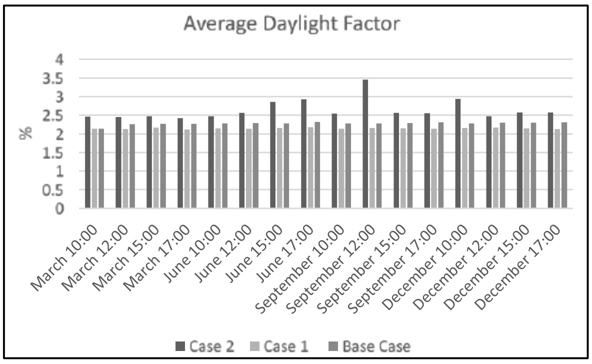


Fig. 4. Average daylight factor Case 2, Case 1, and Base Case

The average increase in daylight factor in March between case 1 (dynamic reflector) and case 2 (static reflector) was 14.5%, while case 1 (dynamic reflector) and the base case was 9.7%. The average increase daylight factor in June between case 1 (dynamic reflector) and case 2 (static reflector) was 25.3%, while case 1 (dynamic reflector) and the base case was 18%. The average increase in daylight factor in September between case 1 (dynamic reflector) and case 2 (static reflector) was 29.2%, while case 1 (dynamic reflector) and the base case was 21.2%. The average increase daylight factor in December between case 1 (dynamic reflector) and case 2 (static reflector) was 22.5%, while case 1 (dynamic reflector) and the base case was 14.8%.

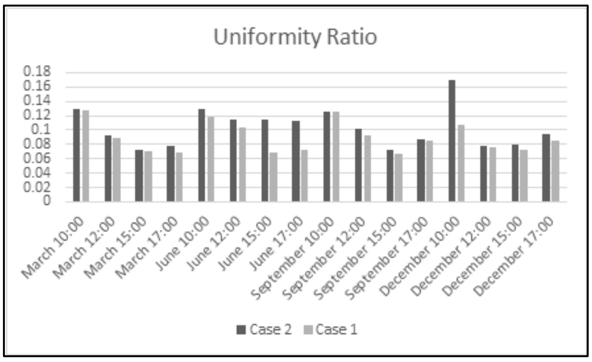
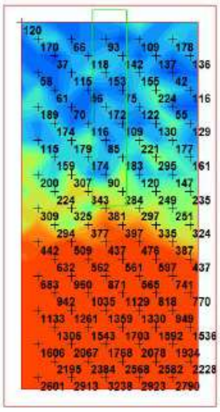
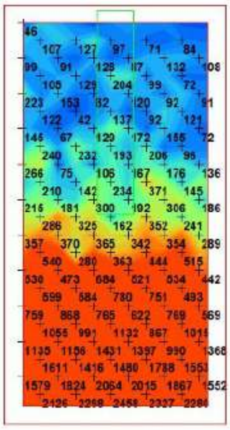


Fig. 5. Average uniformity ratio Case 2, Case 1, and Base Case

The average increase uniformity ratio in March between case 1 (dynamic reflector) and case 2 (static reflector) was 5.1%, while case 1 (dynamic reflector) and the base case was 16.7%. The average increase uniformity ratio in June between case 1 (dynamic reflector) and case 2 (static reflector) was 23.7%, while case 1 (dynamic reflector) and the base case was 33.3%. The average increase in uniformity ratio in September between case 1 (dynamic reflector) and case 2 (static reflector) was 5.5%, while case 1 (dynamic reflector) and the base case was 23.1%. The average increase uniformity ratio in December between case 1 (dynamic reflector) and case 2 (static reflector) was 14.2%, while case 1 (dynamic reflector) and the base case was 28%.

According to a study (Elsiana et al., 2021), integrating the HLP system with shading devices can increase the uniformity ratio value so that a simulation is carried out to compare the uniformity ratio values of dynamic reflectors with shading devices and dynamic reflectors without shading devices. The shading device applied in the simulation is a figure with a length of 150cm and is placed above the side window. This simulation aims to increase the uniformity ratio to a more optimal value.

Table 6. Comparison of the dynamic reflector with shading device and dynamic reflector without shading device

Time	Results	Uniformity Ratio
September 21 10.00	Dynamic reflector without shading device	 UR: 0.126
	Dynamic reflector integrated with shading device	 UR: 0.150

The simulation results show that the addition of a shading device can increase the uniformity ratio and not reduce the amount of light in the room. However, the focus of this research is on the tilt angle of the dynamic reflector so that only one simulation is given for integrating the dynamic reflector with the shading device in the HLP system.

CONCLUSION

The dynamic reflector in the HLP system affects the quality of natural lighting in the office space. As one of the sustainability solutions, the horizontal light pipe system with dynamic reflectors can distribute natural lighting with a depth of more than 11m, namely the Praxis Tower Surabaya office space as a case study. Testing the effect of dynamic reflectors on improving the quality of natural lighting was carried out using the IESVE software experimental simulation method. This study was conducted in a humid tropical climate. The research variables are the angle of incidence of the sun, the angle of inclination of the reflector, the dimensions of the space, the orientation of the openings, the material of the room, the material of the HLP system, the dimensions of the HLP, and the measurement time. With the orientation of the opening facing northwest, the measurement times for this study were March 21, June 21, September 21, and December 21 at 10.00, 12.00, 15.00, and 17.00.

The study's results provide data on the sun's angle of incidence, which varies from 53˚ at 10.00 to 172˚ at 17.00. The data of the angle of incidence of the sun is used for the analysis of the tilt angle of the reflector. The tilt angle movement of the reflector is from 27˚ at 17.00 to 63˚ at 10.00. From the results of the reflector tilt angle analysis, a simulation test was carried out on the quality of natural lighting by comparing the base case (room without HLP system), case 1 (room with HLP static reflector system), and case 2 (room with dynamic HLP reflector system). In case 2, compared to the base case and case 1, there is an increase in the quality of natural lighting every hour, which has been determined as a simulation variable. The highest lighting quality improvement in case 2 is in the table below.

Table 7. Conclusion on improving the daylight quality in the office

No.	Results	Case 2 daylighting enhancements
1.	Illuminance levels	The highest increase in illuminance levels by case 2 (dynamic reflector) was 29.9% compared to case 1 and 29.6% compared to the base case.
2.	Daylight Factor	The highest increase in daylight factor in case 2 reached 29.2% compared to case 1 and 21.2% compared to the base case.
3.	Uniformity Ratio	The highest uniformity ratio increase in case 2 reached 23.7 compared to case 1 and 33.3% compared to the base case.

Modifying the reflector of the HLP system to be dynamic can increase the efficiency of the HLP system's performance. Integration testing of dynamic reflectors with HLP system shading devices is needed in future research to optimize the uniformity ratio value.

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