Daylighting And Lighting Energy Saving In South-Oriented Open-Plan Office With Light Shelf In The Tropics

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Abstract:This paper examined the performance of a light shelf (LS) as a delighting device for reducing electric light usage in a south-oriented open-plan office (OPO) under the sky in the tropic using Integrated Environmental Solution Virtual Environment (IES VE). Results showed that the LS improved daylight quantity of the one-sided light office by reducing the excessive illumination at the area close to the window opening but increased it at the back where the illuminance is low. The improvement at the rear was from 1.55 % (LS 3 at noon on 21st March) to 2.99 % (LS 2 on 22nd June at noon). The LS also improved illuminance uniformity for visual comfort in the room with the best three test cases ranging from 74.07 % (LS 2 and 7) to 76.67 % (L3) compared to the case without LS. The selected test cases showed higher illuminance distribution between adjacent points or possible sitting position in the room than the base case (BC). The reduction in electric light usage ranged from 11.78 % (LS 3) to 15.97 % (LS 2). Hence, the paper concludes that LS improved daylight and electric energy efficiency. Therefore, the LS 2 is recommended for the south-oriented OPO with one-sided lighting in the tropical climate.

Keywords: Daylight, Electric light, Energy efficiency, Light shelf, Tropical climate.

1. INTRODUCTION

Daylighting is an approach in building design that promotes the reduction in the use of electricity in offices [1], especially that work is done in these offices when daylight can be used [2]. There is an abundance of daylight in the region within the tropics[3]- [3-5], without any charge and deleterious effect on human [6]. It has a desirable colour rendering and positive impact on human health and sensibility [2]. Daylight also promotes task performed better than electric light [7].

For places in the tropics, Malaysia inclusive, the outside illuminance can be more than 100 Klx, whereas, this is approximately 20 klx in the temperate climate areas [8]. Despite this high external illuminance in the tropics, designing a building to achieve the desired indoor illuminance is difficult due to high frequency of the formation of cloud that is not easy to predict [9], [10]. High electricity usage in open-plan offices in Malaysia observed by [9], is a pointer to underutilization of daylight.

Open-plan office has gained acceptance by many corporations due to the benefits of large floor area such as flexibility of sitting arrangement, cooperation and collaboration among workers[11], [12]. However, high electricity consumption for lighting is usually associated with this kind of office space because of the difficulty in achieving effective daylight in the deep area of the office [13]. Buildings principally utilize electricity for lighting, cooling and others [14]. The electric consumption of 54 % was attributed to the Malaysia building subsector out of which 33 % was for those used for commercial activities, and the remaining 21 % was for residential [15]. In 2012, residential and commercial buildings consumed 24,707 GWh and 38, 645 GWh of electricity, respectively [16]. The electric energy use in the office for air-conditioner, lighting, office equipment, and others were 52 %, 20 %, 19 % and 9 % respectively [17]. The implication is that a high percentage of electricity is used for lighting in the office, and the impact of daylighting on electric light consumption in the office should be of interest.

According to [18], an office space without partition up to depth ranging from 6 m to 12 m is termed open-plan. A study by [19] used office with 12 m depth in Malaysia as a deep-plan office. Lim [9] arrived at 7.2 m x 9.6 m (width x depth) as the mean size of thirteen open-plan offices studied in Johor, Malaysia. It appears that there is no common ground on the depth of open-plan. Nonetheless, most scholars employed depth below 12 m for open-plan office. Hence, there can be a rationalization that open-plan office should not be deeper than 12 m while office with12 m depth and beyond can be termed as deep-plan. The present study uses office with open-plan, which have 9 m depth focusing on Malaysia.

Lim, et al. [6] stated that unilateral lighting with the sizeable unshaded opening is a common feature of most open-plan offices in Malaysia. Consequently, these office spaces have high illuminance up to 11,193 lux at the work plane near the window opening and very low illuminance at the back with entire room uniformity ratio of less than 0.1 [2]. This high illuminance contrast causes visual discomfort that makes office tenants disallow the available daylight into the room by using blind and depend totally on the electric light [2]. There is, therefore, the need for the introduction of a daylighting system to minimize illuminance at the area near the window and boost it at the back, thus improving the daylight quantity and quality [20], [21].

A light shelf (LS) is one of the light casting devices that is capable of improving daylight in a room and by implication reduces energy usage for lighting [22]. Many research has been done on the light shelf. However, this research was mainly in the temperate region [23], [24]. The daylight in the temperate region is different from that of a place in the tropic like Malaysia. Also, according to [19], most studies on daylighting were with the shallow plan having lighting through one side.

Most studies on the LS focused on daylighting. However, the energy-saving implication of daylight is not unimportant. This is one of the areas of departure of the present study from the previous ones. The mounting height, width of the light shelf as well as the orientation of building affect light shelf performance [25]. External and internal LS, the internal light shelf was used in the previous research works. This study used external and internal light shelf of different tilt angles from clerestory and bottom light shelf.

The aim of this paper is to recommend light that is efficient in terms of daylight and energy for electric light in open-office in Malaysia with south orientation as buildings in the northern hemisphere like Malaysia with this orientation receive daylight for the greater part of the day [19].

2. METHODOLOGY

Simulation with Integrated Environmental Solution Virtual Environment (IES VE) was the main instrument used for data collection. However, the sky model of this software is CIE standard sky which is different from the tropical sky. Hence, it's suitability or otherwise for this study which is under tropical sky ought to be determined.

2.1 Validation of the Software

One office at the Universiti Teknologi Malaysia (UTM) Eco-home was used in the validation of the software. The UTM Johor, Malaysia is located on latitude $1^{o}28'0''$ N and longitude $103^{o}45'$ $0''$E. Two north-east oriented windows of the selected office room devoid of obstruction were used while others were closed with a carton to have unilateral lighting. The roof of the Eco-hone was without obstruction also, which allows the external illuminance to be measured with reliable value.

The dimension of the office space used for this experiment was 3.8 m x 3.5 m x 2.8 m (length x width x height). The length and width are shown in Figure 1a, while the height is shown in Figure 1b. The size of the windows is 0.4 m x 1.350 m (width x height) while the window sill is at 0.9 m from the floor level. The pane of the window used was tinted and had a thickness of 0.4 mm. Two light shelves were fixed to the window to reflect daylight into the room. They were placed by the window at 2.35 m from the ground which is approximately at two-third of the height of the window from its sill. The experiment was carried out on 21st, 25th and 26th January 2018. The illuminance values were taken at 9 am, noon and at 3 pm. Due to software limitation, 15th January was used in the simulation. The external illuminance (P4) and three internal illuminances (P1, P2 and P3) were taking at the same time at work plane height of 0.75 m as presented in Figure 1b also. At a distance a of 1 m from the north-east wall was (P1), the distance of P2 and P3 were 2 m and 3 m from the same wall. The measured illuminance points were at a distance of 1.2 m each from the south-east wall, while Figure 2 showed illuminance meter on the roof for the external illuminance measurement.

The light shelves were made of white foam. This light shelf material with 0.810 reflectances was applied in a study by [26]. The properties of the room surface and the light shelves have a serious effect on the illuminance value [27]. The value of the surface reflectance was obtained through Equation (1) as submitted by [28]. This is the ratio of the illuminance (E1) measured at 2.3'' distance where the light meter faces the surface to the illuminance (E2) measured with a light meter which faces the incident light expressed as a percentage. Table 1 gave a summary of the surface properties.

The illuminance measurement was done with four UA-002-08 Hobo Data Loggers model, which can measure illuminance between 0 to 320 Klx levels. The installed Hobo software in the personal computer was used for setting the date and time for the Hobo Data Loggers to commence reading.

The model of Eco-home was made with the ModelIT module of IES VE with a similar arrangement of illuminance meter, and the simulation was done. The daylight ratio (DR) of the experiment was compared with that of the simulation. The DR is more applicable in the tropic than daylight factor (DF) [29].

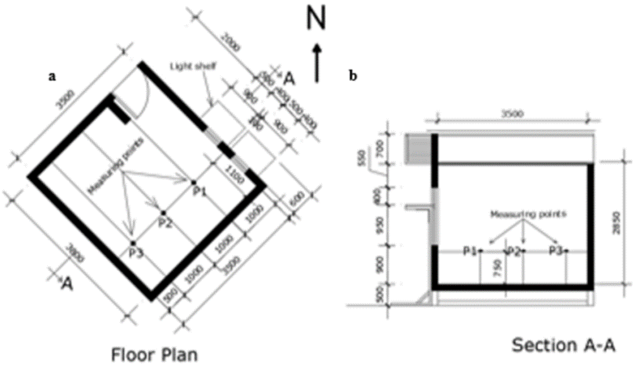


Figure 1: Illuminance Meter arrangement in Plan and Section

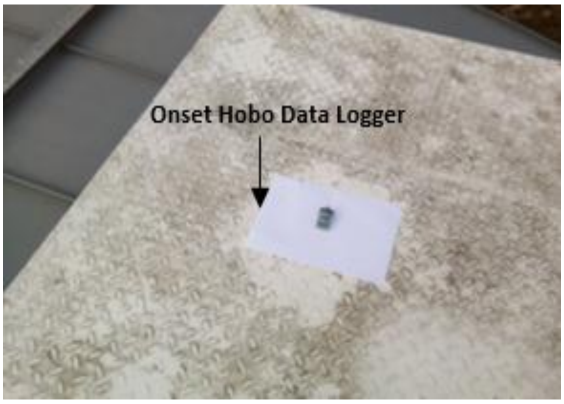


Figure 2: Illuminance Meter on the Roof

$$Surface\ reflectance\ = E\_1/E\_2\ \ x\ 100\ \% \qquad (1)$$

Table 1: Surface properties of UTM Eco-home and the light shelf

Element	**Reflectance**	**Visible transmittance**
Floor	0.552	-
Wall	0.309	-
Ceiling	0.800	-
Door	0.437	-
Light shelf	0.810	-
Windowpane (tinted)	-	38.0%

The comparison of the results was made through Pearson Correlation (r), Root Means Square Error (RMSE) and Mean Bias Error (MBE) using Equation 2, 3, and 4, respectively. The (r) is used to evaluate the relationship regarding two groups of measured values [9]. The closer to 1 and -1, which are the highest values, the stronger the direct relationship and inverse relationship, respectively. The RMSE deals with the level of scattering of the sample, while the MBE concerns the level of the prediction of the samples [30].

$$r = (n(\sum(xy) - (\sum x)(\sum y))/(\sqrt{([n\sum x^2) - \sum x)^2] [n\sum y^2 - (\sum y)^2]}) \quad (2)$$

$$RMSE = \sqrt{((\sum(x-y)^2)/n)} \quad (3)$$

$$MBE = \frac{\sum(x-y)}{n} \quad (4)$$

Where,

Y = value from the simulation, x = value from the experiment and n = measured number

The summary of the result is shown in Table 2. The r-value of the 9 timings is very close to 1. This shows a strong direct relationship between the measured and simulated values. There is no guideline on the feasibility of RMSE and MBE. However, the values obtained in this study is similar to [31], [32]. Therefore, the result of the simulation produced by IES VE in the tropical climate is reliable.

Table 2: Comparison between computer simulation and experiment

Date	**Time (hour)**	**Pearson Correlation**	**RMSE (%)**	**MBE (%)**
22/01/2018	0900	0.9856	7.30	6.70
	1200	0.9977	10.30	10.00
	1500	0.9986	3.83	3.33
Wall	0900	0.9984	8.37	7.33
	1200	0.9783	6.48	6.00
	1500	0.9918	9.64	9.33
Ceiling	0900	0.9820	7.33	8.21
	1200	0.9868	9.50	9.00
	1500	0.9979	9.11	1.54

3. DAYLIGHTING SIMULATION

The dimension of the room which had 9 m depth, 9 m width and 2.7 m height shown in Figure 3 was derived from [9]. The window wall ratio (WWR) of 70 % used was derived from [2], [33], [10], which were studies in the same location. Table 3 gave a summary of the surface reflectance of the room and the light shelf used for this study which was derived from [19].

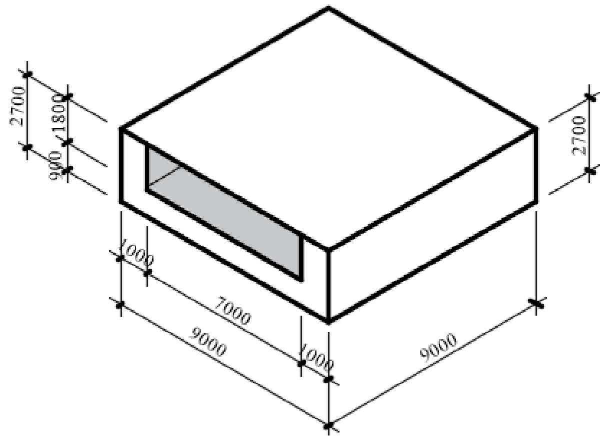


Figure 3: Office Room Geometry

Table 3: Surface properties of UTM Eco-home and the light shelf

Element	Reflectance (%)	Specularity	Roughness	Type	Visible Transmittance
Wall	70	0.03	0.03	Plastic	N/A
Floor	20	0.03	0.20	Plastic	N/A
Ceiling	80	0.03	0.03	Plastic	N/A
Light shelf	90	0.05	0.03	Metal	N/A
Glazing	N/A	N/A	N/A	Plastic	0.75

The worst-case scenario for the BC and 12 LS test cases were observed using 10 Klx overcast skies. The dates applied in simulation with intermediate sky were 21st March, 22nd June and 22nd December. The dates portray the angles of the sun that are critical for the year; equinox, summer and winter solstices correspondingly. Lim [9], submitted that the sun path on the 21st March and 23rd September are identical. Thus, the omission of 23rd September in this research work. The working time in the area of this research is from 8 am to 5 pm. Therefore, 9 am, noon and 3 pm were used as the representative of different solar positions within this time and used in the simulation.

4. LIGHT SHELF CONFIGURATION

Figure 4 showed different light shelf geometries used in the simulation. These light shelves were selected out of 67 cases based on their reflection of direct light into the room. The base case (BC) is without light shelf (LS). The length of all the LS cases is 7 m which corresponds to the width of the window opening. The internal and bottom shelves of LS 1 and 2 were horizontal with a depth of 600 mm. The depth of their external shelves was 900 mm. However, the external shelf of LS1 had 80^{o} as its tilt angle from the clerestory while that 70^{o} was for LS 2.

LS 3 had external and internal shelves of 900 mm depth. The bottom shelf was 600 mm, and it was horizontal alongside with the internal shelf. The depth of the external shelf of LS 4 and 5 was 900 mm, and they were horizontal. Both of these LS had internal and bottom shelves of 600 mm. However, the internal and bottom shelves of LS 4 had a tilt angle of 100^o while those of LS 5 had 110^o from the clerestory.

LS 6 had an external shelf with 900 mm depth and a tilt angle of 80^o from the clerestory. This test case had internal and bottom shelves of 600 mm depth. The internal shelf was horizontal while the bottom shelf had a tilt angle of 100^o from the clerestory. The external, internal and bottom shelves of LS 7 and 8 were 600 mm in depth. The bottom and internal shelves were horizontal. The external shelf of LS 7 had 80^o as its angle of tilt from the clerestory while LS 8 had it's an external shelf at a tilt angle of 70^o from the clerestory. The depth of 600 mm was for external, internal and bottom shelves of LS 9, 10, 11 and 12. The LS 9, 10, and 11 had horizontal external shelves. The bottom and external shelves of LS 9 had 110^o as their angle of tilt from the clerestory whereas LS 10 had a tilt angle 100^o from it. The LS 11 and 12 had horizontal internal shelves while their bottom shelves had 100^o as their tilt angle from the clerestory.

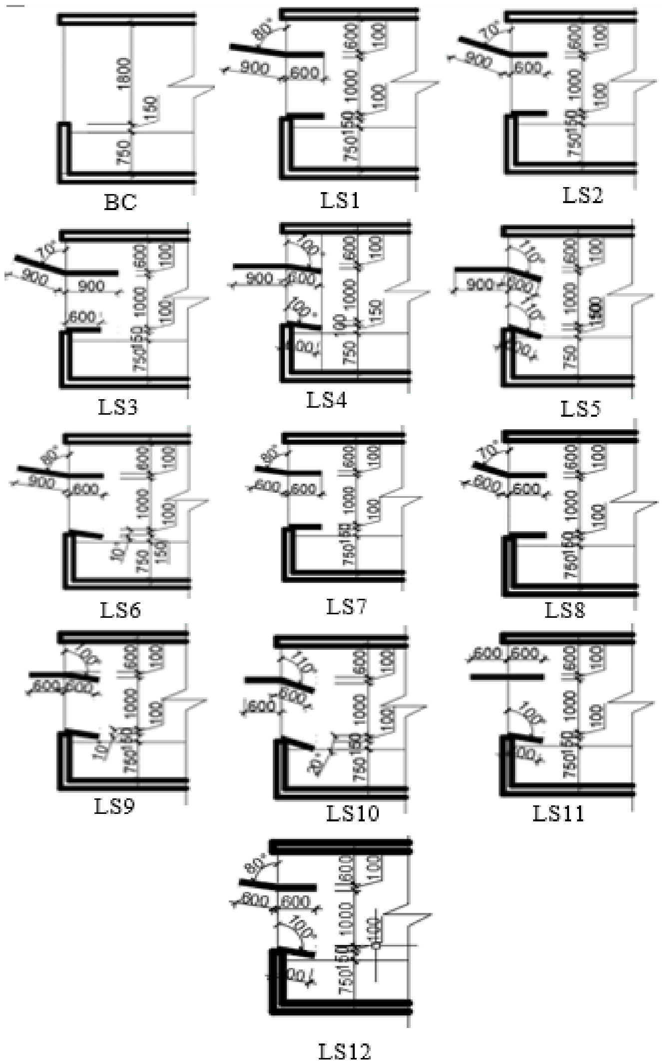


Figure 4: Base case and 12 light shelf test cases

5. PERFORMANCE OF LIGHT SHELF

The impact of LS on the south-oriented open-plan office with the one-side window opening in terms of daylight and saving in electricity for lighting was studied. South orientation was chosen because Malaysia, which is in the northern hemisphere, received sunlight for the greater part of the day than other orientation since the sun path arcs through the south orientation. Perhaps, this is why [25], [7] and [19] used only this orientation in a related study in Toronto, Athens and Malaysia respectively which are located in the northern hemisphere. Room with north orientation will receive less sunlight since the sun path arcs behind the window opening. The East orientation will only receive direct sunlight in the morning while that of west orientation is in the afternoon. The performance criteria used for the analysis include daylight factor (DF), daylight ratio (DR), estimated indoor illuminance (EII), work plane illuminance ratio (WPIR) and electric light consumption.

5.1 Daylight Factor

The performance of the 12 LS test cases and the case without LS in terms of daylight quantity was evaluated with overcast sky using Equation 5. As stated by [8], [34], there is a little occurrence of the overcast sky in the tropics. Nonetheless, this evaluation was done to observe the performance of the light shelf (LS) under the worst situation of the sky. From Table 4, the maximum DF of the BC was 15.56 %. This was far beyond the acceptable range of 1.0 % to 6.0 % DF recommended in Malaysian Standard (MS) 1525:2019. According to this standard, DF above 6.0 % will result in visual and thermal discomfort. All the LS test cases reduced the maximum DF of the room without LS to an acceptable level. The decrease in the DF of the BC by the LS test cases stretched from 80.35 % (LS 6) to 89.72 % (LS 5). Besides, the test cases were equally able to reduce the mean DF of 8.93 % at row 1to 3 of the BC to the range within the benchmark generally. The quantitative daylight performance of the BC and the test cases were further analyzed using DR.

$$DF = (Indoor\ illuminance)/(Ourdoor\ Illuminance) \times 100\% \quad (5)$$

Table 4: Daylight factor of the base case and the LS 12 test cases

Result		Cases						
		BC	**LS1**	**LS2**	**LS3**	**LS4**	**LS5**	**LS6**
DF (%)	Minimum	0.15	0.11	0.07	0.05	0.10	0.10	0.06
	Maximum	15.56	1.61	2.56	2.68	2.08	1.60	2.98
	Row1-3	8.93	0.92	1.31	1.30	1.12	1.10	1.44
	Row1-6	0.87	0.42	0.46	0.46	0.49	0.45	0.49
	Average	0.20	0.13	0.14	0.09	0.13	0.14	0.11
% of changes in DF	Minimum		-26.67	-53.33	-66.67	-33.33	-33.33	-60.00
	Maximum		-89.65	-83.55	-82.78	-86.63	-89.72	-80.85
	Row1-3		-89.70	-85.33	-85.44	-87.46	-87.68	-83.87

Result		Cases						
	Row1-6		-51.72	-47.13	-47.13	-43.68	-48.28	-43.68
	Average		-35.00	-30.00	-55.00	-35.00	-30.00	-45.00
Result		**LS7**	**LS8**	**LS9**	**LS10**	**LS11**	**LS12**	-
DF (%)	Minimum	0.13	0.10	0.10	0.10	0.12	0.12	-
	Maximum	2.20	2.92	2.52	2.64	2.61	2.69	-
	Row 1-3	1.15	1.42	1.33	1.57	1.26	1.31	-
	Row 1-6	0.36	0.46	0.45	0.55	0.38	0.46	-
	Average	0.15	0.14	0.12	0.13	0.15	0.13	-
% of changes In DF	Minimum	-13.33	-33.33	-33.33	-33.33	-20.00	-20.00	-
	Maximum	-85.86	-81.23	-83.80	-83.03	-83.23	-82.71	-
	Row 1-3	-87.12	-84.10	-85.11	-82.42	-85.89	-85.33	-
	Row 1-6	-58.62	-47.13	-48.28	-36.78	-56.32	-47.13	-
	Average	-25.00	-30.00	-40.00	-35.00	-25.00	-35.00	-

5.2 Daylight Ratio

DR of the BC and the test cases was calculated using Equation 6. This Equation is similar to Equation 5. However, DR is only applicable under the climate in the tropic, whereas DF is under the overcast sky [35]. Figure 5 to 7 showed the DR of the BC and test cases under the intermediate sky at 9 am, noon and 3 pm on 21st March, 22nd June and 22nd December. Generally, the outcome revealed that the DR was high in December due to the effect of direct sunlight during winter solstice with the BC having the worst case. The indoor illuminance was highest at 9 am followed by 3 pm and the least was at noon. This was due to the sun angle at the different time of the day. The lower the sun angle, the more the penetration of direct light into the room. The DR was converted to Estimated Indoor Illuminance (EII) for further analysis.

$$DR = (Indoor\ illuminance)/(Ourdoor\ Illuminance) \times 100\% \quad (6)$$

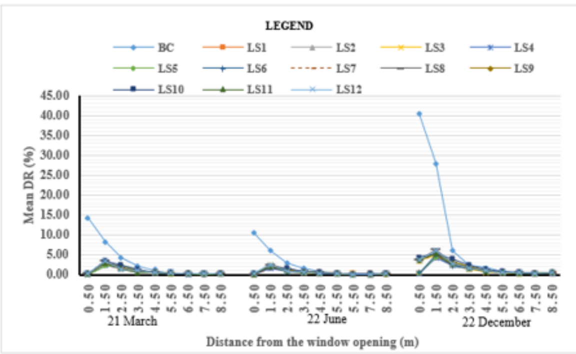


Figure 5**.** Mean DR of the base case and 12 LS cases at row distance of 0.5 to 8.5 m for 21st March, 22nd June and 22nd December, at 9 m.

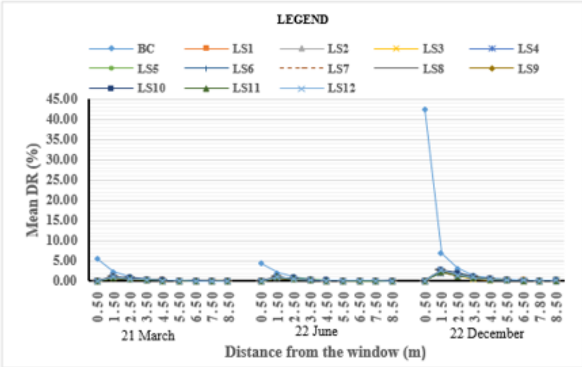


Figure 6. Mean DR of the base case and 12 LS cases at row distance of 0.5 to 8.5 m for 21st March, 22nd June and 22nd December, at noon.

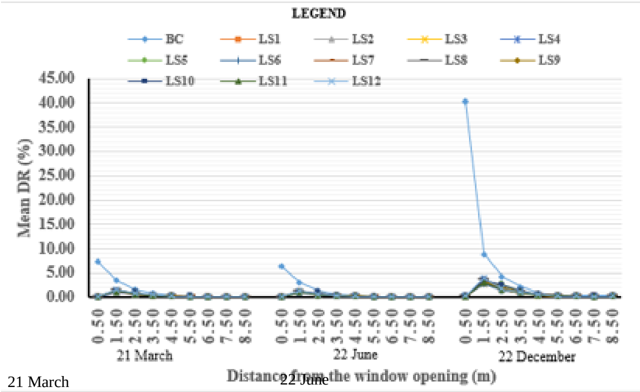


Figure 7. Mean DR of the base case and 12 LS cases at a row distance of 0.5 to 8.5 m for 21st March, 22nd June and 22nd December, at 3 pm.

5.3 Estimated Indoor Illuminance

The Estimated Indoor Illuminance (EII) gives the usability of the indoor illuminance in the room in the tropic, unlike DR, which is about the availability of daylight illuminance [19]. The EII was obtained by the application of Equation 7. The Estimated Outdoor Illuminance was obtained from the experiment for validation. It was 45007.72 lux, 112978.50 lux and 49370.79 lux for the morning, noon and afternoon respectively. Table 5 to 7 showed the average EII for the BC and the test cases for 21st March at 9 am, noon and 3 pm, 22nd June at 9 am, noon and 3 pm and 22nd December at 9 am, noon and 3 pm at row 1 to 3, 4 to 6 and 7 to 9. It also showed the percentage change in the EII of the test cases compared to the BC.

$$EII = \frac{Daylight\ Ratio}{100} \times Est.Outdoor\ Illuminance \qquad (7)$$

Based on the outcome, the percentage decrease in EII which ranged from 77.73 % (LS1 at 9 am on 21st March) to 93.31 % (L1 at noon on 22nd December) was observed for row 1to 3. For row 4-6, there was a decrease in EII, ranging from 8.30 % (LS 8 on 21st March at noon) to 61.26 % (LS 10 at 9 am on 22nd June). Although a decrease in the mean EII was observed at row 7-9 contrary to the expectation in most cases, increase in the average EII at this row was observed which ranged from 1.55 % (LS 3 on 21 March at noon) to 2.99 % (LS 2 at noon on 22 June). This shows that LS can improve illuminance at the back area of the room.

Table 5: Mean EII of row 1-3.4-6 and 7-9 for the BC and the test cases on 21 March at 09:00, 12:00 and 15:00

Time (Hours)	Performance Indicator	Row	Cases						
			BC	**LS1**	**LS2**	**LS3**	**LS4**	**LS5**	**LS6**
09:00	Mean EII (lux)	1 to3	4018.94	603.08	819.08	709.90	649.79	673.24	731.38
		4to6	546.32	293.26	312.18	245.76	313.36	304.89	284.98
		7to9	144.27	112.53	114.11	94.80	101.70	90.66	101.10
	% of increment in mean EII	1 to3		-84.99	-79.62	-82.34	-83.83	-83.25	-81.80
		4to6		-46.32	-42.86	-55.01	-42.64	-44.19	-47.84
		7to9		-21.99	-20.90	-34.29	-29.51	-37.16	-29.92
			LS7	**LS8**	**LS9**	**LS10**	**LS11**	**LS12**	-
	Mean EII (lux)	1 to3	688.41	837.02	758.97	895.16	692.55	749.90	-
		4to6	262.91	301.74	312.38	349.23	228.62	313.56	-
		7to9	120.62	104.06	103.47	92.63	112.14	98.34	-
	% of increment in mean EII	1 to3	-82.87	-79.17	-81.12	-77.73	-82.77	-81.34	-
		4to6	-51.88	-44.77	-42.82	-36.08	-58.15	-42.60	-
		7to9	-16.39	-27.87	-28.28	-35.79	-22.27	-31.83	-
12:00			**BC**	**LS1**	**LS2**	**LS3**	**LS4**	**LS5**	**LS6**
	Mean EII (lux)	1 to3	3351.75	609.64	677.46	523.23	573.62	601.87	614.35
		4to6	317.89	266.32	261.14	231.24	251.02	251.02	275.74
		7to9	103.37	87.36	100.08	104.97	75.82	81.00	90.42
	% of increment in mean EII	1 to3		-81.81	-79.79	-84.39	-82.89	-82.04	-81.67
		4to6		-16.22	-17.85	-27.26	-21.04	-21.04	-13.26
		7to9		-15.49	-3.19	1.55	-26.65	-21.64	-12.53
			LS7	**LS8**	**LS9**	**LS10**	**LS11**	**LS12**	-
	Mean EII (lux)	1 to3	587.27	701.48	544.89	683.82	516.63	619.30	-
		4to6	229.59	291.52	261.85	264.44	238.54	259.49	-
		7to9	78.41	94.66	73.23	73.47	68.76	80.53	-
	% of increment in mean EII	1 to3	-82.48	-79.07	-83.74	-79.60	-84.59	-81.52	-
		4to6	-27.78	-8.30	-17.63	-16.81	-24.96	-18.37	-
		7to9	-24.15	-8.43	-29.16	-28.93	-33.49	-22.10	-
	Mean EII (lux)	-	**BC**	**LS1**	**LS2**	**LS3**	**LS4**	**LS5**	**LS6**
		-	2069.55	321.38	412.08	339.98	319.31	379.89	374.78

Time (Hours)	Performance Indicator	Row	Cases						
			BC	LS1	LS2	LS3	LS4	LS5	LS6
		-	233.61	157.37	160.74	124.96	162.48	141.60	145.52
		-	67.97	52.42	59.38	50.68	47.96	43.83	55.47
	% of increment in mean EII	-		-84.47	-80.09	-83.57	-84.57	-81.64	-81.89
		-		-32.64	-31.19	-46.51	-30.45	-39.39	-37.71
		-		-22.88	-12.64	-25.44	-29.44	-35.52	-18.40
15:00	Mean EII (lux)	-	LS7	LS8	LS9	LS10	LS11	LS12	-
		-	357.92	419.04	366.19	410.78	343.46	400.45	-
		-	146.71	147.37	155.96	156.83	135.19	162.81	-
		-	50.79	51.99	43.72	48.18	47.20	49.48	-
	% of increment in mean EII	-	-82.71	-79.75	-82.31	-80.15	-83.40	-80.65	-
		-	-37.20	-36.92	-33.24	-32.87	-42.13	-30.31	-
		-	-25.28	-23.52	-35.68	-29.12	-30.56	-27.20	-

Table 6: Mean EII of row 1-3.4-6 and 7-9 for the BC and the test cases on 22 June at 09:00, 12:00 and 15:00

Time (Hours)	Performance Indicator	Row	Cases						
			BC	LS1	LS2	LS3	LS4	LS5	LS6
	Mean EII (lux)	1 to3	2955.3	396.97	523.95	512.93	392.14	511.97	463.34
		4to6	412.63	212.01	223.80	159.83	237.91	220.33	195.01
		7to9	116.15	90.84	80.79	75.18	70.93	57.59	80.79
	% of increment in mean EII	1 to3		-86.57	-82.27	-82.64	-86.73	-82.68	-84.32
		4to6		-48.62	-45.76	-61.26	-42.34	-46.60	-52.74
		7to9		-21.80	-30.45	-35.27	-38.94	-50.42	-30.45
09:00									
			LS7	LS8	LS9	LS10	LS11	LS12	-
	Mean EII (lux)	1 to3	459.20	603.77	568.79	566.85	474.47	556.61	-
		4to6	218.78	235.98	240.62	201.96	187.47	183.99	-
		7to9	70.54	69.58	59.53	86.78	72.28	62.62	-
	% of increment in mean EII	1 to3	-84.46	-79.57	-80.75	-80.82	-83.94	-81.17	-
		4to6	-46.98	-42.81	-41.69	-51.05	-54.57	-55.41	-
		7to9	-39.27	-40.10	-48.75	-25.29	-37.77	-46.09	-
			BC	LS1	LS2	LS3	LS4	LS5	LS6
	Mean EII (lux)	1 to3	2866.82	505.45	615.07	531.61	503.21	557.02	568.98
		4to6	339.29	248.87	251.61	209.01	204.03	242.89	262.82
		7to9	114.59	91.67	118.02	97.15	85.70	67.01	100.39
	% of	1 to3		-82.37	-78.55	-81.46	-82.45	-80.57	-80.15

12:00	incremen	4to6		-26.65	-25.84	-38.40	-39.87	-28.41	-22.54
	in mean EII	7to9		-20.00	2.99	-15.22	-25.22	-41.52	-12.39
			LS7	**LS8**	**LS9**	**LS10**	**LS11**	**LS12**	-
	Mean EII (lux)	1 to3	479.05	625.53	535.10	607.65	507.45	580.19	-
		4to6	233.17	252.85	228.69	245.63	191.57	211.00	-
		7to9	91.67	84.70	76.73	72.74	71.75	97.90	-
	% of incremen in mean EII	1 to3	-83.29	-78.18	-81.33	-78.80	-82.30	-79.76	-
		4to6	-31.28	-25.48	-32.60	-27.61	-43.54	-37.81	-
		7to9	-20.00	-26.09	-33.04	-36.52	-37.39	-14.57	-
15:00	Mean EII (lux)	-	**BC**	**LS1**	**LS2**	**LS3**	**LS4**	**LS5**	**LS6**
		-	1793.65	285.93	385.15	343.02	276.79	304.44	308.36
		-	217.80	143.73	146.35	115.72	129.49	135.19	152.40
	% of incremen in mean EII	-	67.77	52.58	61.01	48.43	48.66	46.29	45.34
		-		-84.06	-78.53	-80.88	-84.57	-83.03	-82.81
		-		-34.01	-32.81	-46.87	-40.54	-37.93	-30.03
		-		-22.42	-9.98	-28.55	-28.20	-31.70	-33.10
	Mean EII (lux)	-	**LS7**	**LS8**	**LS9**	**LS10**	**LS11**	**LS12**	-
		-	298.98	336.96	319.63	373.53	294.95	361.06	-
		-	131.15	148.01	148.48	145.28	109.31	130.44	-
		-	47.83	50.32	43.92	39.17	41.19	50.92	-
	% of incremen in mean EII	-	-83.33	-81.21	-82.18	-79.17	-83.56	-79.87	-
		-	-39.78	-32.04	-31.83	-33.30	-49.81	-40.11	-
		-	-29.42	-25.74	-35.20	-42.21	-39.23	-24.87	-

Table 7: Mean EII of row 1-3.4-6 and 7-9 for the BC and the test cases on 22 December at 09:00, 12:00 and 15:00

Time (Hours)	**Performance Indicator**	**Row**	**Cases**						
			BC	**LS1**	**LS2**	**LS3**	**LS4**	**LS5**	**LS6**
09:00	Mean EII (lux)	1 to3	11184.35	1079.94	1852.50	1671.02	1034.67	1204.88	1122.50
		4to6	764.20	476.43	525.59	397.74	480.32	516.46	466.72
		7to9	252.40	171.57	156.80	162.05	161.08	184.59	170.60
	% of incremen in mean EII	1 to3		-90.34	-83.44	-85.06	-90.75	-89.23	-89.96
		4to6		-37.66	-31.22	-47.95	-37.15	-32.42	-38.93
		7to9		-32.02	-37.88	-35.80	-36.18	-26.87	-32.41
			LS7	**LS8**	**LS9**	**LS10**	**LS11**	**LS12**	-
	Mean EII (lux)	1 to3	1718.82	1949.84	1848.03	2049.38	1723.67	1888.64	-
		4to6	530.06	527.92	594.18	668.99	464.97	500.53	-
		7to9	170.02	179.15	172.74	202.08	169.63	188.86	-

Time (Hours)	Performance Indicator	Row	Cases						
			BC	**LS1**	**LS2**	**LS3**	**LS4**	**LS5**	**LS6**
	% of increment in mean EII	1 to3	-84.63	-82.57	-83.48	-81.68	-84.59	-83.11	-
		4to6	-30.64	-30.92	-22.25	-12.46	-39.16	-34.50	-
		7to9	-32.64	-29.02	-31.56	-19.94	-32.79	-25.17	-
12:00			BC	LS1	LS2	LS3	LS4	LS5	LS6
	Mean EII (lux)	1 to3	19701.37	1317.96	1663.87	1411.28	1430.55	1593.36	1529.71
		4to6	1076.78	628.93	587.59	459.78	592.92	674.07	608.13
		7to9	287.33	200.85	230.27	200.34	182.08	206.94	194.51
	% of increment in mean EII	1 to3		-93.31	-91.55	-92.84	-92.74	-91.91	-92.24
		4to6		-41.59	-45.43	-57.30	-44.94	-37.40	-43.52
		7to9		-30.10	-19.86	-30.27	-36.63	-27.98	-32.30
			LS7	**LS8**	**LS9**	**LS10**	**LS11**	**LS12**	-
	Mean EII (lux)	1 to3	1463.01	1676.80	1552.50	1855.59	1371.21	1654.99	-
		4to6	578.97	618.28	652.26	739.24	557.66	597.73	-
		7to9	177.27	214.55	205.16	226.46	158.25	209.47	-
	% of increment in mean EII	1 to3	-92.57	-91.49	-92.12	-90.58	-93.04	-91.60	-
		4to6	-46.23	-42.58	-39.43	-31.35	-48.21	-44.49	-
		7to9	-38.31	-25.33	-28.60	-21.18	-44.92	-27.10	-
15:00	Mean EII (lux)	-	**BC**	**LS1p**	**LS2**	**LS3**	**LS4**	**LS5**	**LS6**
		-	8798.50	746.30	893.93	809.11	784.51	959.34	719.35
		-	606.71	333.09	348.55	296.12	336.43	409.13	368.95
	% of increment in mean EII	-	202.03	113.13	112.39	86.67	121.66	108.56	112.51
		-		-91.52	-89.84	-90.80	-91.08	-89.10	-91.82
		-		-45.10	-42.55	-51.19	-44.55	-32.57	-39.19
		-		-44.00	-44.37	-57.10	-39.78	-46.27	-44.31
	Mean EII (lux)	-	**LS7**	**LS8**	**LS9**	**LS10**	**LS11**	**LS12**	-
		-	829.76	1008.92	915.20	1056.28	784.63	968.24	-
		-	321.59	371.67	376.37	438.44	290.31	329.38	-
		-	107.45	122.53	108.81	122.78	98.79	93.10	-
	% of increment in mean EII	-	-90.57	-88.53	-89.60	-87.99	-91.08	-89.00	-
		-	-46.99	-38.74	-37.97	-27.74	-52.15	-45.71	-
		-	-46.82	-39.35	-46.14	-39.23	-51.10	-53.92	-

5.4 Illuminance Distribution on the Work Plane

The illuminance uniformity using the ratio of minimum to the mean illuminance in the room ($E_{min}/E_{average}$) and the percentage of adjacent possible sitting positions in the room that got

WPIR $E_{min}/E_{max} \geq 0.5$ at work plane height of 0.75 m were evaluated for optical comfort.

Figure 8 showed the spreading of the illuminance in the room without LS and the LS integrated room on 21st March, 22nd June and December at 9 am, 12 noon and 3 pm. The BC manifested the least distribution for these days and time. Lower distribution of daylight was exhibited by the test cases in March and December than in June. The lower direct sunlight penetration into the room in June during summer solstice compared to the period of equinox in March and winter solstices in December are the reasons for this occurrence.

The uniformity of 0.36 in the room was portrayed by LS 3 on 22nd June at 3 pm and this was the highest. LS 7 and 2 had illuminance distribution of 0.34 and 0.33 on 22nd June and at 3 pm also. Next to these first three top test cases in terms of illuminance uniformity was LS 1that got 0.31 at noon on 21st March and 22nd June. This test case also had 0.31 at 3 pm on 22nd December and 21st March. The remaining test cases had daylight distribution of less than 0.31for the room.

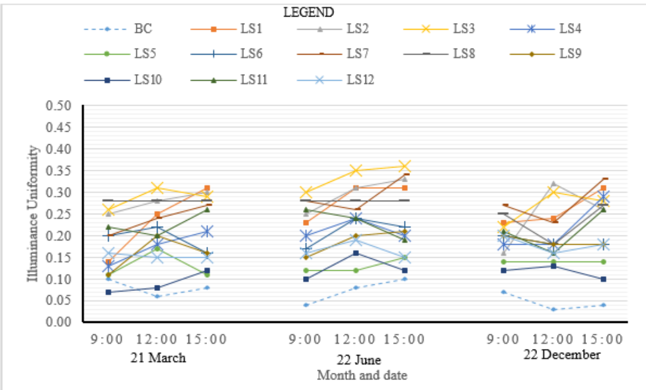


Figure 8. Illuminance uniformity for the whole room using $E_{min}/E_{average}$ for the BC and 12 LS test cases on 21st March, 22nd June and 22nd December at 9 am, noon and 3 pm.

Figure 9 showed the adjacent points that had ≥ 0.5 in terms of percentage using minimum illuminance per maximum illuminance (E_{min}/E_{max}) to obtain WPIR for the LS test cases and the BC at 9 am, noon and 3 pm on 21st March, 22nd June and 22nd December. These points are possible sitting positions in the office room. The were thirty-six points which represent possible sitting positions in the office room created by using the grid of 1.5 m x 1.5 m with the offset of 0.75 m from the wall surfaces at work plane height of 0.75 m. The result showed that the BC and LS 12 got 51.67 % at 3 pm with LS 10 at 9 am as their minimum percentage of points that achieved the benchmark.

At noon, on 22nd June the BC had 68.33 % as the maximum value of adjacent points that achieved the benchmark, that of LS 10 was 75.00 % on 22nd December at 9 am while LS 12 had 78.33 % on 22nd December at noon. At 9 am, 3 pm on 21st March and at 9 am on 22nd June, LS 5 had 53.55 % as the minimum value of the percentage of points that achieved the benchmark. This value was the same for LS 9 on 21st March at 9 am. LS 5 had 71.67 % as the maximum percentage of adjacent points that had $E_{min}/E_{max} \geq 0.5$ benchmark on 22nd June at noon and at 9 am on 22nd December whereas in the cases of LS 9, it was 80.00 % at noon on 21st March and 9 am on 22nd December. This test case was next to the highest in terms of the percentage illuminance distribution between the adjacent points.

At 9 am on 22nd June, LS 3 and LS 11 had 55.00 % and 51.67 % respectively as the percentage of points that are adjacent to each other with WPIR of minimum illuminance per maximum illuminance greater or equal to 0.5. At noon on 22nd June, LS 6 had 85.0 0% as the maximum percentage of adjacent points that had 0.5 and above WPIR using minimum illuminance per maximum illuminance which was the highest of all the test cases while this cases had 58.33 % as the minimum percentage on 21st March at 9 am and at 3 pm on 22nd December. 78.33 % of points adjacent to one another had WPIR using minimum illuminance per maximum illuminance equal to or greater than 0.5 for LS 1 at noon on 22nd June whereas the minimum percentage was 48.33% at 9 am on 22nd June also. This test case had the least percentage of the adjacent point that achieved the benchmark.

For LS 4 and LS 2, the minimum percentage of point with WPIR of minimum illuminance per maximum illuminance greater or equal to 0.5 was 58.33 % and 63.33 % at 9 am on 22nd June whereas the maximum value of 78.33 % was observed at 9 am on 22nd for LS2 and also at 9 am on 22nd December for LS 4. In the case of LS 7, 75.00 % was the maximum percentage of the points that achieved the benchmark on 22nd December at 9 am and 55.00 % was the minimum percentage of points at 9 am on 21st March. For LS 8, 73.33 % was the maximum percentage of points that got the minimum illuminance per maximum illuminance greater or equal to 0.5 at noon on 22nd June and 22nd December at 9 am while the minimum percentage was 55.67 % at noon on 21st March.

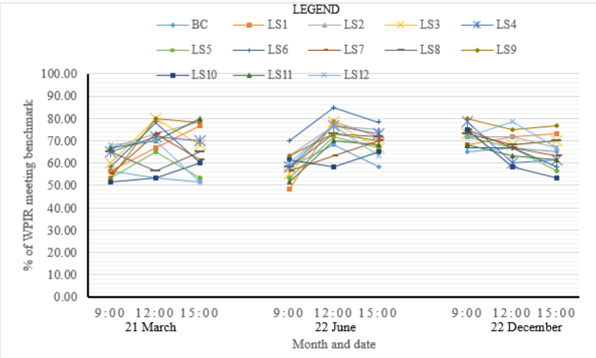


Figure 9 Illuminance uniformity Using $E_{min}/E_{min} \geq 0.5$ for the BC and 12 LS cases on 21st March, 22nd June and 22nd December at 9 am, noon and 3 pm

5.4.1 Comparison of Minimum/average WPI Ratio and Minimum/ Maximum WPI Ratio of the Adjacent Points

The illuminance distribution by the cases regarding the whole room and between the possible sitting positions (adjacent points in the room) was done. Generally, the illuminance distribution of the BC was poor because there was no LS to intercept, reflect as well as distribute daylight from the sun or sky into the room. The summary of the cases with the best performance is given in Table 8 based on their mean performance for the 9 timings.

The illuminance of 0.3 for the whole room was attributed to LS 3 which was the highest of the best three cases. LS 2 and 7 had 0.27 which were next to LS 3. Nonetheless, there was more consistency in the uniformity of LS 7 based on the three months and 9 timings than LS 2. Therefore, LS 7 outperformed LS 2 in terms of illuminance uniformity in the entire room. For the percentage of WPIR between possible sitting position or points adjacent to each other using minimum illuminance per maximum illuminance greater or equal to 0.5 benchmarks, LS 3 achieved the highest which was 70 %. This was followed by LS 2 which had 66.67 % and LS 7 which had 63.33 %.

Table 8 Summary of shelf cases with the best WPIR based on the mean values

LS cases	WPIR for the entire room	% of adjacent points that met WPIR benchmark
LS2	0.27	66.66
LS3	0.30	70.00
LS7	0.27	63.33

6. ENERGY CONSUMPTION OF THE LS CASES

The LS test cases with the best daylighting performance were examined for their electric light energy efficiency. This was done by comparing the electric light energy consumption of the LS integrated room with the BC. The method of dimming electric light as the daylight in the room increases: ramp (e1, 0, 1, 300, 0) in IES VE was employed. With this formula, when there is no daylight, the electric light will be fully on and as the daylight penetration into the room increases, the electric light reduces until the required daylight of 300 lux is achieved. This illuminance level was set based on the lower limit of the illuminance range in Malaysian Standard (MS 1525:2019), then the electric light will be automatically turned off. Following the recommendation of the said standard, 14 W/m^2 light power density (LPD) for office was used.

The electric energy usage for light was studied with the BC, LS 7, LS 3 and LS 2. The result showed that the BC consumed a total of 2.2913 kW of energy based on the consumption of 0.7683 kW, 0.7769 kW and 0.7461 kW on 21st March, 22nd June and 22nd December respectively. The electric light energy consumption observed on 21st March was 0.6420 kW, that of 22nd June was 0.6549 kW and it was 0.6276 kW on 22nd December, giving a total consumption of 1.9253 kW for the three days for LS 2. For LS 3, 2.013 kW was the total energy consumed as 0.6783 kW, 0.6869 kW and 0.6561kW of electric light energy consumption were observed on 21st March, 22nd June and 22nd December respectively. For LS 7, on 21st March, the energy consumption was 0.6552 kW, it was 0.6956 kW on 22nd June and that of 22nd December was 0.6531 kW, totalling 2.0039 kW for these days. From these results, the percentage decrement in energy use attributable to LS 3 in comparison with the BC was 11.78 % which was the lowest of these three best test cases, the next was LS 7 with 12.54 % and LS 2 was able to reduce the energy consumption by 15.97 % which had the best energy-saving performance as shown in Table 9.

Table 9 Daylight and Energy Performance of selected Light Cases

LS Cases	Estimated indoor Illuminance	WPIR for the entire room	% of adjacent points that met WPIR benchmark	% of electric energy saving
LS2	highest	0.27	66.66	15.97
LS3	moderate	0.30	70.00	11.78

LS7	lowest	0.27	63.33	12.54

The highest performance in daylight quantity was shown by LS 2. This was because this test case was able to reduce excessive illuminance at the area close to the window and also relatively improved it at the back. The next test case to this was LS 3 while LS 7 had the least performance among the three cases selected. The WPIR of 0.27 using minimum illuminance per average illuminance across the room was exhibited by LS 7 and LS 2 which was lower than 0.30 achieved by LS 3. The LS 7 got 63.33 % as the percentage WPIR of points adjacent to each other with minimum illuminance per maximum illuminance equal to or greater than 0.5 which was lower than 70.00 % and 66.66 % achieved by LS 3 and 2 respectively. LS 7 also performed moderately in terms of energy efficiency by reducing consumption by 12.54 %. Hence, the best case was not LS 7. Even though LS 3 had WPIR of 0.3 in the whole room and 70.00 % between adjacent points which showed better uniformity than LS 2 and LS 7, it had the poorest percentage in the reduction in energy usage of 11.78 %. Therefore, the best case was not LS 3. LS 2 achieved the same uniformity ratio of 0.27 at work plane across the whole room alongside with LS 7.

Further, LS 2 had 66.66 % as the percentage of points adjacent to each other with $E_{min}/E_{max} \geq$ o.5 which was a decent performance. This test case had the highest quantitative performance. Moreover, it got 15.97 % as the reduction in electric energy usage for lighting which was the highest efficiency among these cases. Thus, the test case with optimum performance in terms of daylight and reduction in electric energy usage for lighting was LS 2.

7. DAYLIGHT AND ELECTRIC LIGHT INTEGRATION IN OPEN-PLAN OFFICE FOR TASK PERFORMANCE

The undesirable daylight condition of the BC observed in the simulation result will make the office users avoid the available daylight and depend on electric light during the hours of work. Consequently, there will be a high consumption of electricity for lighting. On the contrary, with the integration of LS into the room, there was an improvement in the quantity and quality of daylight with the resultant effect of reduction in electric light usage.

As a strategy to reduce electric energy usage in the office room, the front, middle and back zone can be created. The space from the window up to 3 m away makes the front zone, the next 3 m is the middle zone, and the last 3 m is the back zone, as indicated in Figure 10. Additional shading is required in the area with illuminance beyond 500 lux as this is more than the level required for any task. The zone having EII ranging from 300-500 lux can be used for reading which requires concentration. The zone that has 100-300 lux can be for work that involves the use of computer since high illuminance is not required for the use of Visual Display Terminal. The zone that has EII less than 100 lux cannot be used for any task as this is too low. Hence, Permanent Supplementary Artificial Lighting (PSALI) is required.

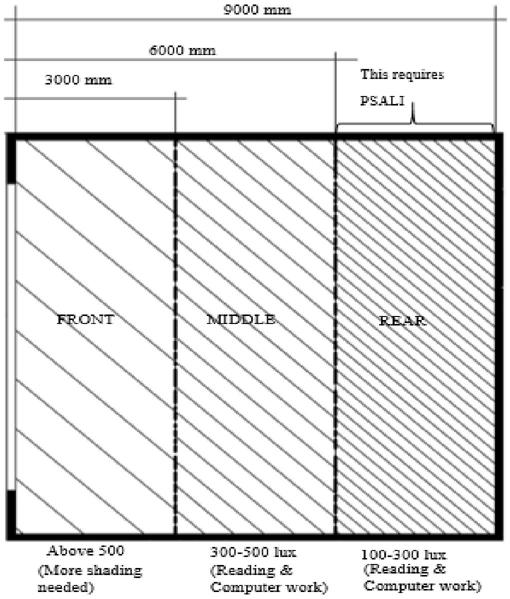


Figure 10 Light zones based on task performance

8. CONCLUSION

Proposing a light shelf that is efficient in terms of daylight and energy for electric light is the focus of this paper. The outcome of this work revealed high contrast in illuminance level in the open-plan office without LS. This was due to high illuminance and low illuminance at the area close to the window opening and the rear respectively. This causes discomfort visually and makes office occupants avoid the available daylight by polling down the curtain and depend on electricity for lighting. Hence, a set of LS was configured and studied with IES VE for their performances in terms of daylight and energy efficiency. The DF, DR, EII, WPIR were the daylight performance indicators used. The outcome showed improvement in daylight quantity and distribution at the work plane in comparison with the BC. Also, reduction in the use of electricity for lighting was observed in the LS integrated office room.

Light shelf was able to reduce the excessive illuminance quantity beyond useful level at the area close to the window and increased low illuminance at the rear area with improvement ranging from 1.55 % (LS 3 on 21 March at noon) to 2.99 % (LS2 at noon on 22 June).

The LS was able to improve visual comfort in the room. This improvement among the best selected three test cases ranged from 74.07% (LS 2 and 7) – 76.67 % (LS 3) in comparison with the BC. Also, the selected test cases had higher illuminance distribution between the adjacent points or possible sitting position in the room than the BC. This improvement ranged from 7.12 % (LS 7) to 18.40 % (LS 2).

The integration of the light shelf with the open-plan office brought about reduction in the use of electricity for lighting as a consequence of the improvement in daylight when compared with the BC. The reduction of 11.78 % (LS 3) – 15. 97 % (LS 2) is the range of improvement.

The focus of this paper is to study the effect of a set of light shelf configuration on the delight and electric energy consumption situation in the open-plan office room in the tropical region. The result showed that LS 2 achieved the best performance in terms of energy-saving and daylight quantity but had moderate performance in illuminance distribution. Hence, the choice of LS 2 was a compromise between daylight and saving in electricity for lighting. LS 2 which is the optimum case is presented in Figure 11. It improved daylight quantity and had 74.07 % improvement in WPIR in the room in comparison with the BC as well as improved WPIR between adjacent points in the room by 2.50 %. Moreover, it had 15.97 % savings in electric energy for lighting which was the highest of all the test cases.

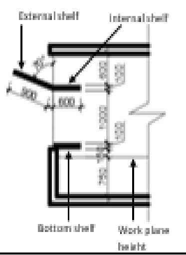
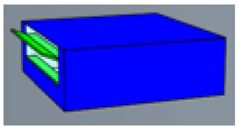
LS Case	2D	3D
LS 2		

Figure 10 Recommended LS

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