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Determination of Design Solutions to Overcome the Daylighting Design Failure Observed in Existing Educational Building

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Abstract: Malaysia is blessed with abundant natural light throughout the year. However, as buildings absorb heat from it, the amount of energy required for cooling purposes increases, which is one of the causes of electricity consumption. This research focused on investigating daylight level with a variety of case study classroom characteristics that contribute to daylighting design failure factors. Hence, indoor and outdoor daylight levels were measured for five (5) days in each of the classrooms through field measurement method. The observation was conducted simultaneously with the field measurement to assess the obstacles to implementing efficient daylighting strategies in the classrooms. The results show that the daylight performance for all of the case study classrooms was not within the prescribed suitable range as specified in MS1525 (2019). The classroom design is insufficient to manage daylight in classrooms, which is the most likely reason for the poor illuminance level results. Furthermore, the amount and performance of daylight in the classroom are influenced by the classroom's specific design. The main factors leading to design failures, according to the observation analysis are poor classrooms orientation, double-loaded buildings with single-loaded windows, small glazing areas, low window placement, inappropriate glazing properties, and low light reflectance value. Based on the failure criteria stated, the best practices of classroom daylighting design were found. Furthermore, this study makes a few recommendations to increase the daylight value in all classrooms. This research identified problems that impact low daylight performance in educational buildings and should be used to raise awareness of the benefits of daylight for occupants.

Keywords: Daylight, Daylighting design, Field measurement, educational buildings, Classroom

1. Introduction

This research focuses on the issue of sustainability and, it is linked with SDGs (Sustainable Development Goals) by United Nations. Sustainability is a subject that is discussed regularly in today's culture. Hence, the sustainability agenda in developing countries focuses on the association between construction and human evolution and poverty alleviation. Some countries, including Malaysia, have already taken steps to make the construction more sustainable to benefit the people. The Malaysian government has highlighted Malaysia's environmental strategies and priorities by introducing a range of national energy policies and a five-year Malaysian strategy (Abdellah et al., 2019). The implementation of SDGs in Malaysia is basically aligned with the five-year development plan and begins with the Eleventh Malaysia Plan (11th MP: 2016-2020), Twelfth Malaysia Plan (12th MP: 2021-2025) and Green Tech Master

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Plan (GTMP: 2017-2030). The five-year plan of Malaysia's medium-term development strategies specifies macro-economic growth goals and the scale and distribution of public sector development programs. It also sets out the indicative role envisioned for the private sector.

Previous researchers have identified several obstacles to sustainable building growth which are lack of knowledge, inadequate information and, construction maintenance and operational expenses are rising significantly per year (Jaafar et al., 2007 & Shaikh et al., 2017). It is because 90% of people invest much of their time in buildings, rendering them the core and most complex component of the indoor design system (Shaikh et al., 2017). In order to overcome these obstacles, researchers acknowledge that passive design is an effective strategy on early stage of planning and designing.

Passive design is a strategy that will maintain resilience, improve construction performance, decrease electricity usage, and minimise CO_2 emissions (Fadzil & Byrd, 2012). The passive design maximises the use of 'natural' means of heating, cooling, and ventilation to establish relaxing environments inside buildings. Tatarestaghi et al. (2018) affirmed that passive design would be taken out at the initial stage of planning and architecture.

Passive design strategies, particularly the application of daylighting, are among the main techniques to moderate illuminance levels and temperatures in buildings (Aflaki et al., 2012). Furthermore, daylighting is a source that can create an enjoyable visual environment for occupants and reduce artificial lighting energy consumption (Mirrahimi et al., 2013). Hence, artificial lighting also dissipates waste heat into the building space, contributing to heating or cooling. However, solar energy's efficient use can significantly reduce the energy required to heat, cool, and light buildings (Galatioto & Beccali, 2016).

This research focus on one of the passive design aspects, daylighting, to reduce lighting consumption occurred. According to the BSEEP (2013), daylighting is consistently available starting 8 a.m. till 6 p.m. However, as buildings absorb heat from it, the amount of energy required for cooling purposes increases, which is one of the causes of electricity consumption. One of the significant buildings in lighting energy consumption is an education building (Dixit & Sudhakar, 2014). The university has to invest a substantial amount of money on an annual basis to sustain electricity use. It has wide construction areas and facilities spanning from classrooms, corridors, shops, libraries, and laboratories (Abidin et al., 2019). It is why most of the electricity has been invested in systems, such as lighting and air conditioning. A study by Othman et al. (2017) claimed that artificial lighting during the daytime occurred in many buildings, especially government and university buildings in Malaysia.

The study findings by Susan and Prihatmanti (2017) indicated that the daylighting penetrating the classrooms was below the norm due to the multiple obstructions generated in both schools; thus, artificial lighting was used as an add-on throughout the school hours because of the uneven spread of daylighting. Susan and Prihatmanti (2017), and Othman et al. (2017) concluded that artificial lighting is one of many building's main sources of electricity consumption. Therefore, the goal of this research is to investigate the daylighting design failures in existing educational buildings and gives recommendations towards the design failures. Failures may be attributed to the passive daylighting design failure. Finding the causes of failures is important and eliminating or reducing them will be impossible at best before the causes are identified. This research is being conducted in conjunction with 11^{th} MP: 2016-2020, 12^{th} MP: 2021-2025, and GTMP: 2017-2030.

2. Literature Review

'Failure' in this study refers to the problems or lack of daylighting design in an educational building, particularly a classroom. The classroom design will be analysed to recognise the failure. Building design failure occurs when the building loses its ability to perform its designated function (Ellingwood et al., 2007). Therefore, 'failure' is detected when there is a lack of daylighting in the studied classrooms during the daytime.

2.1 Daylighting

Daylighting is an important factor in the design of education buildings as it creates a pleasant environment, promotes healthier conditions, and ensures energy saving (Michael & Heracleous, 2016). Excessive daylight may be unwanted and may cause glare problems. Glare measures an occupant's physical discomfort induced by excessive light or contrast in a particular sector. It depends on the distribution of luminance in the observer's field of perspective (Jakubiec & Reinhart, 2011).

MS1525 (2019) stated that there are four (4) types of sky condition, namely standard overcast, cloudy, intermediate, and clear blue sky. Malaysia can be assorted as intermediate sky conditions, which are sky mostly covered with cloud almost 30.0% to 70.0%, of which 85.7% of the time the atmosphere is cloudy and 14.0% overcast (Zain-Ahmed, 2000). Tropical climates are often characterised by long sunlight hours, making it easier to increase energy output by daylight (Fitriaty et al., 2019).

A building's cautious architectural design helps maximise natural light while preserving indoor temperature regulation and reducing light glare. Before incorporating comprehensive daylighting characteristics into a building, architects are orienting the structure to maximise daylight potential, taking into account the sun's daily motion

(Christian & Barbara, 2012). It is not only creating the optimal application of daylighting that requires zero electricity, but it can also bring to life other essential aspects of a building, such as architecture, colour, and textures.

2.1.1 Guidelines for Daylighting in Buildings

Various standards and guidelines on daylighting consideration have been developed in Malaysia, including the MS1525, highlighting the recommended illuminance level for learning spaces. In contrast, the Uniform Building by Law (UBBL) recommends the WFR for learning spaces. However, the recommended WFR may not achieve the recommended illuminance level (Syaheeza et al., 2018). Others, such as MS1525, Public Works Department (PWD), and Illuminating Engineering Society of North America (IESNA), recommend the same illuminance level of 300lux to 500lux for a common reading task in general teaching spaces, as shown in Table 1.

Table 1 – Illumination Level Recommendations (Syaheeza et al., 2018)

Learning Space	Standards and Guidelines		
	MS1525	**JKR**	**IESNA**
General Teaching Space	300-500	300-500	300-500
Science Laboratories	300	300	500
Library	300-500	300	300

2.1.2 Daylighting Calculation

Daylight Factor (DF) measures a reference point in the daylight available indoors versus the daylight available outdoors during a cloudy sky setting (Nedhal et al., 2016). The DF is described as an indicator to evaluate the perceived levels of internal illuminance on working planes or surfaces that are simple to understand, easy to use, and of fair reliability for Malaysia's tropical climate. Equation 1 shown as DF formula as indicated by MS1525 (2019):

$$DF = \frac{E_{internal}}{E_{external}} \times 100\% \qquad (1)$$

Section 39(3) of UBBL provides that any room or space that serves the purpose of learning and educational space should be constructed for natural lighting and natural ventilation with a minimum of 20.0% of WFR. There are two ways used to measure the percentage of glazing. WFR is the proportion arising from the division of the building's overall glazed region by the overall floor space. The WFR should be open to unrestricted natural airflow at no less than 10%. Equation 2 describes the total percentage of WFR based on glazing area and gross interior floor area (Zain-Ahmed et al., 2002). However, the WWR is the complete region of the window separated by the wall (ASHRAE, 2004). WWR is a significant attribute influencing the energy efficiency of buildings. Equation 3 describes the total percentage of WWR based on wall area and gross exterior wall area.

$$\text{WFR (\%)} = \frac{\sum \text{Glazing area (m2)}}{\sum \text{Gross interior floor area (m2)}} \qquad (2)$$

$$\text{WWR (\%)} = \frac{\sum \text{Glazing area (m2)}}{\sum \text{Gross exterior wall area (m2)}} \qquad (3)$$

2.1.3 Malaysia Climate Conditions

Malaysia is located in the southeast part of Asia and lies in a geographic coordinate of 2° 30' North latitude and 112° 30' East longitude. Malaysia generates much daylight all year round. According to the Malaysian Meteorological Department (Met Malaysia, 2019), Malaysia's climate characteristics are uniform temperature, high humidity, and plenty of rainfall. Malaysia is very uncommon in the equatorial doldrums to have a clear sky even in serious drought periods. Malaysia is also rare to have a multi-day period with no sunlight except during the north-eastern monsoon season.

A guideline for sky illuminance provided by the Building Energy Efficiency Technical Guideline for Passive Design stated that the Malaysian tropical climate is ideal for daylight harvesting in buildings as daylight is available daily from 8 am to 6 pm. Because Malaysia is near the equator, there is hardly any seasonal variation that changes the daylight's daily accessibility. In terms of daylight, Malaysia receives plenty of natural light throughout the year. The Malaysian sky condition is classified as intermediate or average, whereby 85.7% of the time, the sky is cloudy and 14%

overcast.

2.1.4 Previous Research Conducted on Malaysia of Daylighting Design Issues

Daylighting's overall intention is to reduce the amount of artificial light and diminish the cost of electricity, but it can also minimise Heating, Ventilation, and Air Conditioning (HVAC) costs. Electrical lighting generates much heat, while natural lighting produces scarcely any heat when properly managed. While daylighting can provide multiple positive occupants performance outcomes, it can produce negative results if a daylighting system has not been appropriately implemented.

Table 2 - Daylighting Design Issues in Malaysia Based on Previous Researchers

Bil.	Researchers	Issues
1	Lim et al., 2012	Daylight did not penetrate at the back of spaces.
2	Lim & Ahmad, 2013	High daylight level due to orientation.
3	Fadzil et al., 2012	The building was overheated due to the glazing area.
4	Mathalamuthu et al., 2014	Uneven daylight due to unsuitable design.
5	Sadin et al., 2014	Illuminance at the back of the rooms was low due to increase room depth.
6	Arab, 2015	High extent of sunlight penetrations in the early morning and late evening.
7	Jamaludin et al., 2015	Higher mean illuminance values were recorded in the corridor to compare the rooms.
8	Mahdavi et al., 2015	East-west had high illuminance compared to north-south.
9	Kamaruzzaman et al., 2015	Inadequate daylighting. Help from artificial lighting. Depth of the room too great.
10	Fadzil & Al-Absi, 2016	The smaller size of the light well caused a dark area.
11	Lim & Heng, 2016	Large glazed façade without shading. Non-uniform distribution. High illuminance. Glare.
12	Susan & Prihatmanti, 2017	Low light level due to obstruction.
13	Othman et al., 2017	Low illuminance due to window design, use artificial lighting.
14	Arabi et al., 2017	Low illuminance due to the size of the opening.
15	Syaheeza et al., 2018	High illuminance, not uniformly distributed due to no external shading and blind.

Table 2 shows the most common issues in a tropical climate which are not enough light due to the inappropriate opening orientation, causing glare because of excessive sunlight. Controlling glare is an important point. Direct sunlight penetration in classrooms also leads to an uncomfortable glare on work surfaces, making it tough to work or display a computer screen. In addition, daylighting often allows the amount of heat to enter a building. Since the sun is such a strong source of light for buildings, it can also produce tremendous amounts of heat. Natural lighting, if not properly designed, can result in unwanted heat gains.

3. Methodology

This research consists of two methods to achieve the research objectives, which are through field measurement and observation. The observation is done to observe building elements and the surrounding area of the existing building. There were six (6) factors focusing on accomplishing the research objective, as shown in Table 3. Hence, the different classroom design characteristics were observed based on those six (6) factors.

Table 3 - Suggested Checklist Items for Daylighting Design Factors

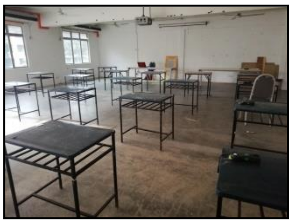
Checklist	Building Form	Building Orientation	Window Design	Reflectance	Special Elements	Obstruction
Items	• Site size and shape • Building size and shape • Depth of	• Building facing • North / South • East/West	• Position • Size • Shape	• Colour of surfaces • Material of surfaces • Arrangement of furniture	• Overhang • Light shelves • Louvres • Blind • Tinted	• Trees • Facade

	room • Height of room

3.1 Case Study Classrooms Characteristics

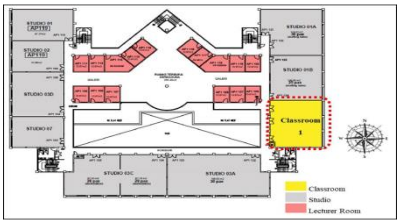
Based on the observation analysis as shown in Table 4, three (3) examined classrooms at an educational building were chosen, and all of the selected classrooms were chosen according to their availability.

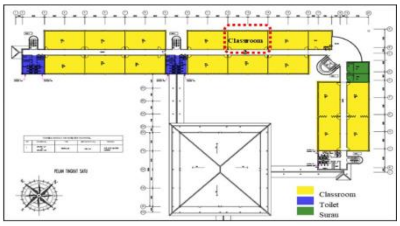
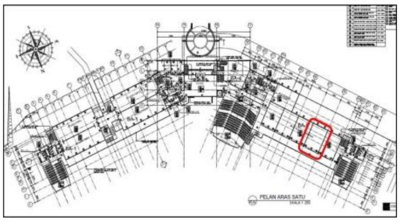
Table 4 – Selected Case Study Classrooms

Classrooms	Outdoor view	Indoor view	Classroom location	Year of construct
Classroom 1			First floor level	2000
Classroom 2			First floor level	2001
Classroom 3			First floor level	2010

The chosen studied classroom is located on the first floor and is the only classroom on that floor. The classroom selection for this building is based on the classroom availability for an observation. The first floor was selected, indicating a low level for daylight to penetrate space.

Table 5 - Case study classrooms characteristics

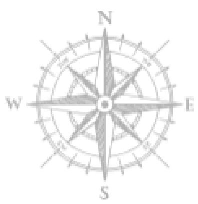
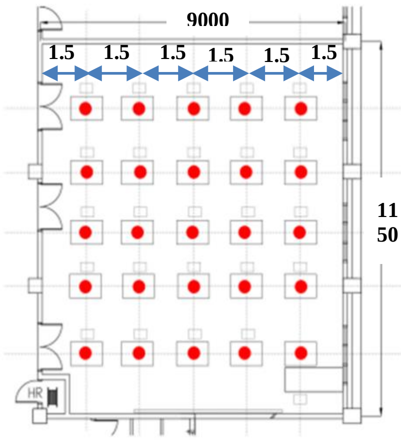
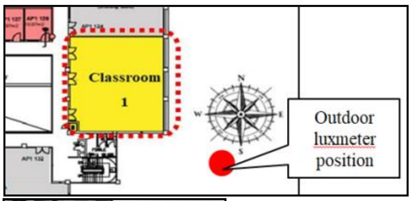
Classrooms	Façade Design	Shading	Size
Classroom 1 	Single-sided window (tinted glazed- East) and single-loaded corridor	No shading	11.5 meter (length) x 9 meter (width)

Classroom 2			
	Single-sided window (tinted glazed-Northwest) and double-loaded corridor	No shading	12 meter (length) x 6 meter (width)
	Double-sided window (clear glass-Southwest & Northeast) and single-loaded corridor	No shading	10.65 meter (length) x 7.2 meter (width)

3.2 Field Measurement Study

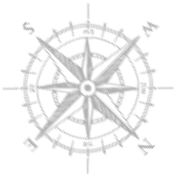
Field measurements of indoor and outdoor parameters will conducted on the studied classrooms within two (2) months (July and August). Measurements will be carried out for each classroom from 8 a.m. till 5 p.m. for five (5) days. The measurements will be taken in all of the selected classrooms to identify the insufficient illuminance levels in each one, which has proved daylighting failures at the first stage of the investigation. Measurements of indoor and outdoor will be carried out on a sunny day with an overcast sky condition, and the instruments will be measured at desk-height level, which is 0.75 metres. The number of measurement points is based on daylighted zones and distance from the window. Indoor and outdoor illuminance measurements were performed on the same day and time every 30 minutes during the daytime. The observation method was used as the second method to determine the daylighting design failures. Table 6 shows the summary of fieldwork measurement procedure for each of the classroom.

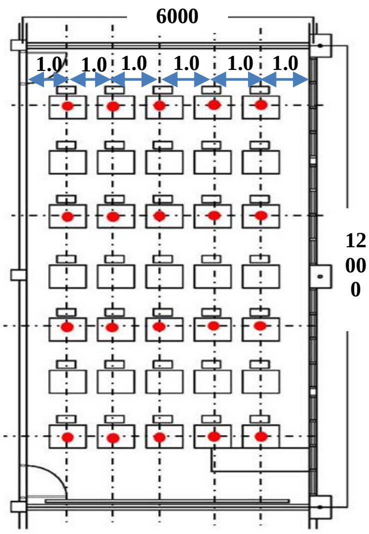
Table 6 – Fieldwork measurement location

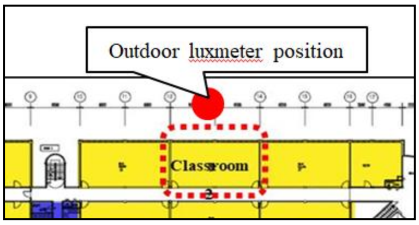
Classrooms	Indoor	Outdoor	
Classroom 1 25 points GFA = 103.5m^2 Height = 3.2m 			
			Placed outside of classroom at open place free from any obstruction (maximum sunlight).

Classroom 2

20 points
GFA = 72.0m^2
Height = 3.2m

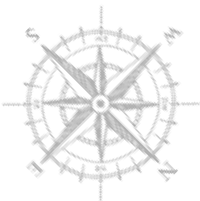


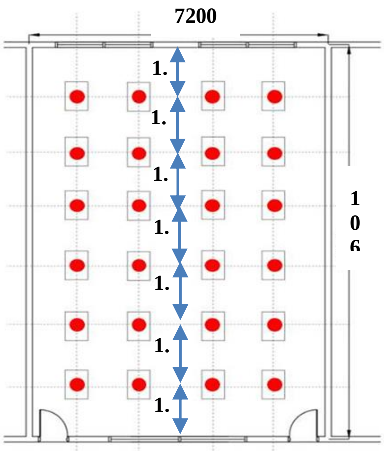


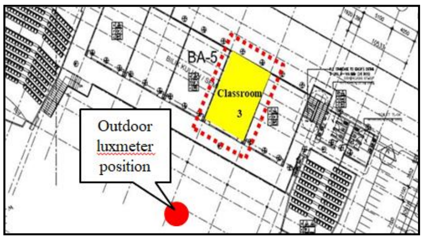


Classroom 3

24 points
GFA = 76.3m^2
Height = 3.0m







4. Results and Discussion

4.1 Results of Fieldwork Measurement

The analysis results are discussed according to average five-day measurement. Hence, the analysis results also cover the daylight factor (DF), window-to-floor ratio (WFR), and window-to-wall ratio (WWR) for each studied classroom.

Table 7 – Average indoor and outdoor illuminance level (lux)

Day	Classroom 1		Classroom 2		Classroom 3	
	Indoor	Outdoor	Indoor	Outdoor	Indoor	Outdoor
Day 1	22 – 1,672 lux	6,983 – 70,910 lux	15 – 121 lux	2,915 – 98,300 lux	306 – 3,055 lux	6,219 – 82,520 lux
Day 2	33 – 2,214 lux	3,815 – 88,750 lux	19 – 326 lux	3,449 – 85,540 lux	304 – 2,546 lux	5,535 – 81,400 lux
Day 3	23 – 1,256 lux	3,471 – 70,260 lux	12 – 313 lux	481 – 85,870 lux	293 – 3,974 lux	5,638– 89,380 lux
Day 4	28 – 1,654 lux	4,199 – 84,500 lux	14 – 315 lux	496 – 85,885 lux	315 – 2,598 lux	6,714 – 84,025 lux
Day 5	30 – 1,656 lux	4,214 – 84,515 lux	20 – 401 lux	3,482 – 88,260 lux	309 – 2,592 lux	6,699 – 84,010 lux

Average	27 – 1,690 lux	4,536 – 67,419 lux	16 – 295 lux	2,615 – 81,495 lux	305 – 2,953 lux	6,616 – 82,853 lux
Total average	**162 lux**	**37, 797 lux**	**85 lux**	**41,395 lux**	**899 lux**	**44,796 lux**

According to MS 1525 (2019), the recommendation for indoor illuminance is within 300 lux to 500 lux. While, to be categorised as intermediate for Malaysia sky type, outdoor illuminance must be between 30, 000 to 100,000 lux. Table 7 shows that overall average indoor illuminance in Classrooms 1 and 2 was below the acceptable level, while Classroom 3 was above it. Furthermore, the total average outdoor illuminance for all classrooms fell under Malaysia's intermediate sky type.

Table 8 – Average Daylight Factor (DF) value

Day	Classroom 1	Classroom 2	Classroom 3
Day 1	0.1 % - 6.2 %	0.1 % - 0.6 %	0.7 % - 8.0 %
Day 2	0.1 % - 8.2 %	0.1 % - 1.2 %	0.8 % - 7.0 %
Day 3	0.1 % - 4.4 %	0.1 % - 1.53 %	1.0 % - 15.0 %
Day 4	0.1 % - 5.4 %	0.1 % - 1.5 %	1.0 % - 10.1 %
Day 5	0.1 % - 5.4 %	0.1 % - 1.1 %	1.0 % - 10.1 %
Average	0.1 % - 5.9 %	0.1 % - 1.19 %	0.9 % - 10.0 %
Total average	**0.5%**	**0.3%**	**2.7%**

The acceptable values, as recommended by MS1525:2019 is between 1.0 % to 3.5 %, so that the lighting, glare, and thermal comfort in the spaces are acceptable. Table 8 shows that only average DF value for Classroom 3 was within the recommended value, whereas Classrooms 1 and 2's DF values were below the classroom's minimum acceptable range.

Table 9 – WFR and WWR value

Classrooms	Glazing Area (m^2)	Gross interior floor area (m^2)	Gross exterior wall area (m^2)	WFR (%)	WWR (%)
Classroom 1	6.48m^2	103.50m^2	36.8m^2	6.26m^2	17.61m^2
Classroom 2	11.52m^2	72.0m^2	38.4m^2	16.0m^2	30.0m^2
Classroom 3	6.09m^2 (northeast) 12.19m^2 (southwest)	76.68m^2	24.48m^2	23.85m^2	24.88m^2 (northeast) 49.80m^2 (southwest)

According to UBBL 1984, WFR and WWR must not be less than 20%, and a ratio less than 20% would most likely result in insufficient daylighting at the back of the room. Table 9 indicates that only the WFR and WWR values in Classroom 3 met the desired value. WFR for Classroom 2 is lower than the recommended value stated by UBBL: 1984, while it is slightly good for WWR because windows with a WWR greater than 30% can cause the building to overheat. The percentage of WFR for Classroom 3 is 23.85%, higher than the recommended value stated by UBBL: 1984. Meanwhile, the percentage of WWR for windows facing northeast is 24.88%, within the recommendation. In comparison, the percentage of WWR for windows facing southwest is 49.80%, greater than 30% allowing more light and heat to enter the room, causing overheating and glare.

4.2 Results of Observation Analysis

Table 10 – Summary of Observation Results

	Building form	Orientation	Window design	Reflectance	Shading	Obstruction
Classroom 1	Single loaded corridor and window with centre courtyard.	Windows facing East	Nine (9) panels of windows vertically with tinted glazed.	White surfaces of ceiling and wall but dark surfaces for floor (dark grey).	No shading devices on façade but tinted film on glazing.	No obstruction for first floor level.
Classroom 2	Double loaded corridor but single sided window.	Windows facing Northwest	Sixteen (16) panels of windows vertically with tinted glazed.	White surfaces of ceiling and wall but dark surfaces of floor tiles (dark grey).	No shading devices on façade but tinted film on glazing	No obstruction for first floor level.
Classroom 3	Single loaded corridor with double sided window.	Windows facing Southwest and Northeast.	Eight (8) panels on Northeast and 16 panels on Southwest with clear glass.	White surfaces of ceiling, wall and floor tiles.	No shading devices on façade and glazing is clear glass.	No obstruction for first floor level.

Based on Table 10, there are six (6) factors focused on during observation. Classroom 1 is a single-loaded corridor with a central courtyard that will invite daylight if a double-sided window is installed. While Classroom 3 had an advantage due to the double-sided windows, the overall average illuminance level was greater than 500 lux, which is insufficient for a classroom of this size. Second, building orientation, Classroom 1 received morning sunlight, Classroom 2 evening sunlight, and Classroom 3 both morning and evening sunlight.

Third, window design includes the size and shape of the window, as well as its position and glazing type. In comparison to the other two classrooms, the glazing area in Classroom 3 is significantly larger and higher up on the wall. All classrooms were initially clear glass, however for Classrooms 1 and 2, a black tinted film was used to prevent heat and glare while also lowering the illuminance level. Next, reflectance refers to the colour and material of surfaces. Classroom 3 has an advantage since all of the interior surfaces are brightly coloured, which means it reflects more light.

Last factors are shading devices. So, Classrooms 1 and 2 have no shading devices on the façade but the tinted film on the glazing, which explains why the illuminance level was lower than recommended, however Classroom 3 has no shading devices at all, which explains why the illuminance level was greater, causing glare and heat problems. Obstruction factor are not counted because it is part of research scope and it has been filtered at the beginning of research.

4.3 Discussion and Recommendations

4.3.1 Classroom Orientation

Table 11 – Observation Analysis on Orientation

Classroom 1	Classroom 2	Classroom 3
Classroom 1 is facing east. The highest indoor illuminance level result is 394 lux in the morning., and the range of illuminance level for five (5) days is 33-394lx.	Classroom 2 is facing northwest. The highest illuminance level result is 309 lux in the evening, and the range of illuminance level for five (5) days is 13-309lx.	Classroom 3 is facing northeast and southwest. The highest indoor illuminance level result is 1094 lux, and the range for five (5) days is 349-1094lx.

Classroom 1 faced east and received varying amounts of daylight during the day, with the highest amount of daylight in the morning due to the single-sided windows facing northwest. Classroom 2 faced exactly northwest, considered as west-facing, received high daylight value in the late afternoon. In contrast, Classroom 3 was north-south facing, and the daylight value was constantly high throughout the day. The principle of a good orientation is to avoid exposure of openings to the intense solar radiation from east and west (MS1525:2019; BSEEP: 2017). It can be concluded that all the three classrooms have a different orientation, and the recommended orientation is facing to the north and south, in relation to a west-east axis, but limit the exposure to the east and west due to the uneven daylight value throughout the day.

Therefore, it can be concluded that the best practice of building orientation benefitting from daylighting is by facing north and south rather than east and west. The east orientation receives direct sunlight in the morning, and the west orientation receives direct sunlight in the afternoon. Since thermal loads peak during the afternoon hours, the west orientation is considered the worst in terms of thermal comfort and solar heat gain. This statement is concurred by BSEEP (2017) and MS1525 (2019) under the principle of passive design elements for a good building orientation. Facing north and south is suggested for the classroom orientation, and only Classroom 3 followed the recommendation to optimise daylight benefit. In contrast, Classroom 1 was facing east, and Classroom 2 technically was facing west. The findings showed that both classrooms received varying daylight levels throughout the day. The best recommendations for both classrooms to obtain a balanced daylight distribution throughout the day are shading devices and external obstructions. Classroom 1 received moderate morning sunlight, and it is highly recommended an external obstruction, such as small trees and shrubs, because the sun is low in the sky. Classroom 2 received afternoon sunlight, and it is strongly recommended an external shading device or internal shading (blind) with a good insulator because the sun is high in the sky and provides heat.

4.3.2 Building Form

Classrooms 1 and 3 were single-loaded buildings, whilst Classroom 2 was a double-loaded building. Classroom 3 had a significant benefit in terms of inviting daylight into the classroom. It is because Classroom 3 was a single-loaded building and provided windows on opposite walls, maximising the amount of daylight. Furthermore, a maximum floor width of approximately 8 metres and a ceiling height of 2.7 metres are required for sufficient daylight (Ibrahim & Hayman, 2010). According to observation, Classroom 1 is more than 8 meters, larger than the other two classrooms, which is why the daylight value was lacking at the back of the classroom. In addition, the observation showed that Classroom 2 had a smaller floor base area compared to Classrooms 1 and 3, giving better advantages for daylighting. Classroom 3 also had a smaller size area than Classroom 1 but bigger than Classroom 2. Research by Ander (2003) stated that a less width floor base area maximises the sunlight into the interior spaces.

A few suggestions to increase illuminance levels through building form; Classroom 1, make it a double-sided window because the current design is a single-loaded corridor to use the centre courtyard. Because of the double-loaded corridor, it is advised that Classroom 2 utilise a tabular daylighting system, whereas Classroom 3's current design is acceptable.

4.3.3 Window Design

Table 12 – Observation Analysis of Window Design

	Classroom 1	Classroom 2	Classroom 3
Size and shape	Nine (9) vertical window panels. The size of one (1) panel is 0.6m x 1.2m.	16 vertical window panels. The size of one (1) panel is 0.6m x 1.2m.	Eight (8) horizontal window panels. The size of one (1) panel is 0.6m x 1.27m.
Position/location	One-sided windows, facing east.	One-sided windows, facing northwest.	Two (2) sided windows, facing northeast and southwest.
Glazing	Black tinted film.	Black tinted film.	Clear glass.

Classroom 3 has a suitable window design for daylighting. It provides windows on both sides of the building façade and uses clear glass glazing, which is good for maximising daylighting but allowing heat and glare penetration. Baker and Stemeers (2002) explained that the opening height and width should be bigger to increase daylight into a building. If the window position is at the side, it should be located as high as possible. Besides, tall windows provide better penetration because the area is high up on the wall, and the amount of daylight penetrates the space depends on the type of glazing. Black tinted film for Classroom 1 and 2 are installed on the window glass. It is the main reason why the lack of daylight penetrating both classrooms.

4.3.3.1 Window Head Height to Room Depth Ratio

According to Ibrahim and Hayman (2010), the room width is 2.5 times the window head height under overcast skies. The width of the daylighted zone for all the classrooms was calculated using the same formula and compared with the indoor illuminance level, as illustrated in Figures 1, 2 and 3.

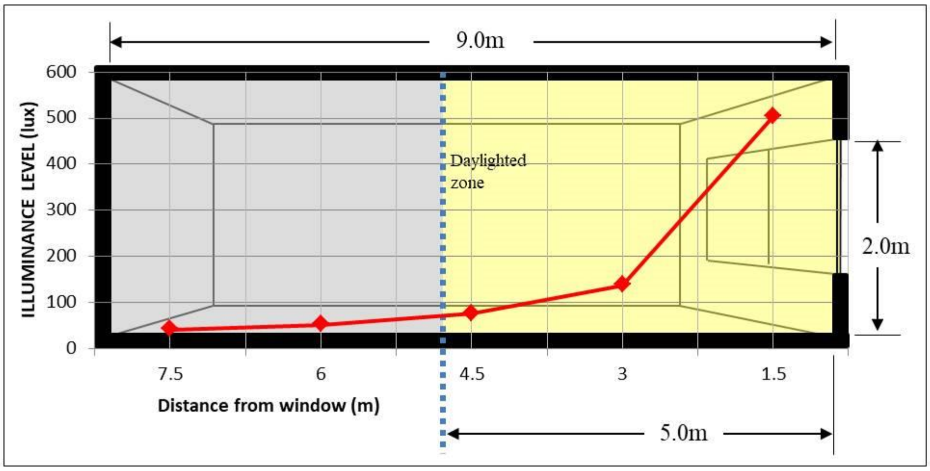


Fig. 1 - Daylighted zone and indoor illuminance level for Classroom 1

Classroom 1 had a width of 9.0 metres and a window head height of 2.0 metres. The daylighted zone was 5.0 metres from the windows and was located in the classroom centre using the rule of thumb formula. Based on the illuminance level, the daylight level decreased as it is farther away from the windows. As a result, Figure 1 reveals that the daylight level was low at the back of the classroom when the width was more than 5.0 metres, with a window head height of 2.0 metres for Classroom 1.

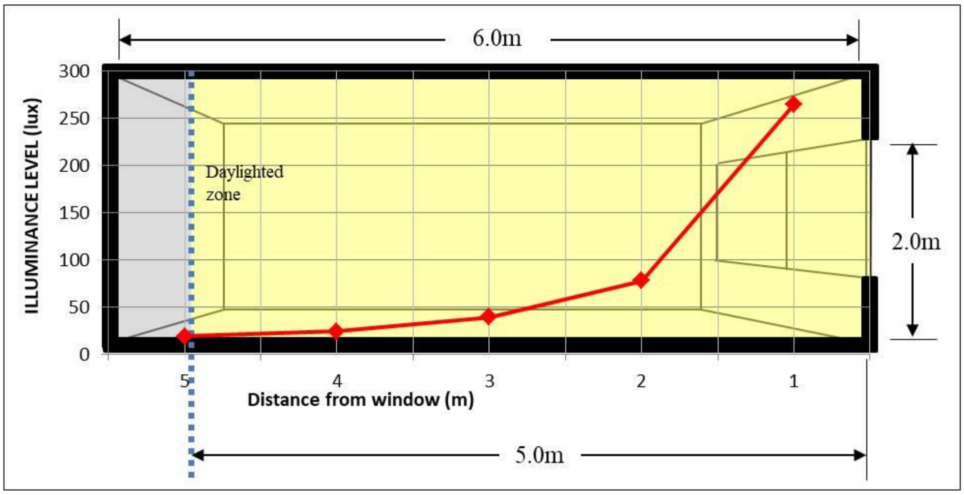


Fig. 2 - Daylighted zone and indoor illuminance level for Classroom 2

Classroom 2 is narrower than Classrooms 1 and 3, with a width of just 6.0 metres, and the daylighted zone is 5.0 metres from the windows, almost illuminate the whole area in Classroom 2. However, the indoor illumination level in Figure 2 revealed that Classroom 2 did not get as much daylight as it should have, and the daylight level also decreased as it got further away from windows due to single-sided windows. Therefore, it is possible to assume that this classroom's window head height and width were not the causes of the low daylight level.

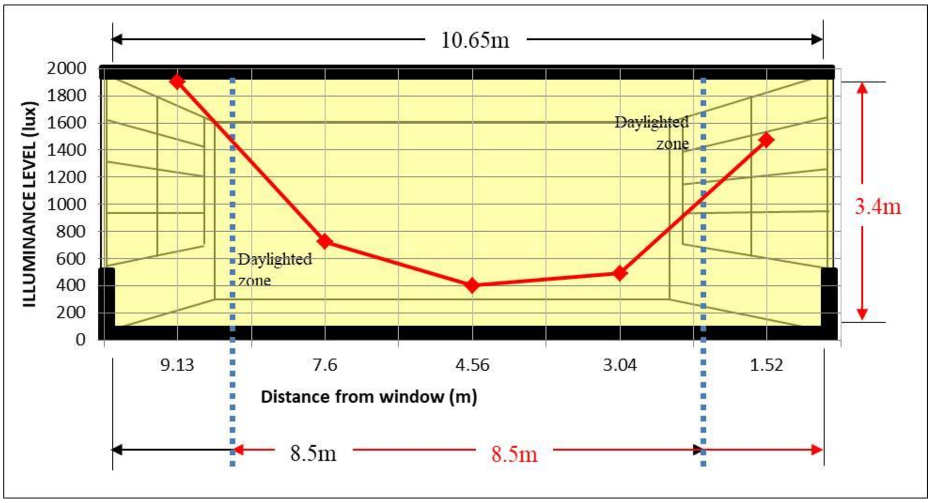


Fig. 3 - Daylighted zone and indoor illuminance level for Classroom 3

Classroom 3 had windows on all opposite walls. Therefore, this classroom could obtain 8.5 metres of daylight from a single-sided window only using the rule of thumb calculation for window height. As shown by the illuminance level in Figure 3, the daylight was abundant on both sides of the windows; only points at the centre of the classroom falling within the recommended range of 300 to 500 lux. Besides, Classroom 3 benefitted from inviting a high amount of daylight into spaces; it exceeded the standards, affecting thermal aspects and glare issues. To conclude, this classroom's width and window head height were sufficient, although it had a wide glazing area provided for both sides of the walls. According to Passive Design Guidebook (2013) by BSEEP, the full floor-to-ceiling height windows do not improve the depth of daylight harvested but increase heat gain in the building while also increasing visual discomfort due to the higher contrast ratio.

According to WFR and WWR values, Classroom 3 had a sufficient size of window area for floor and exterior wall area given. Classroom 2 had a low WFR value but a sufficient WWR value, whereas Classroom 1 had low WFR and WWR values, and it is suggested to increase the glazing area for both classrooms. Concerning Classrooms 1 and 2, it is recommended that these classrooms install more windows opposite the current window to ensure there is no gloomy area at the back of the classrooms. In other words, the opposite windows should be applied in Classroom 1 and 2, similar to Classroom 3. Next, it was recommended that the windows be placed high up on the window wall. It is necessary because the high window placement can be used to project light deep into rooms (Carvalho & Pedrini, 2014). According to the window head height to room depth ratio, the existing window placement for Classroom 3 was sufficient to tackle maximum daylight value. However, the windows in Classrooms 1 and 2 were suggested to be lifted to the top of the ceiling, from 2.0 metres to 3.2 metres; hence, increasing the daylighted zone and projecting light deep into rooms

The next recommendation was the type of glazing on building façades. The type of glazing depends on building orientation and space function. Classrooms 1 and 2 had a clear glass but tinted with a black film reducing the heat absorption and glare problems, but at the same time reducing daylighting level. If these two (2) classrooms change the glazing to clear glass, the heat and glare issues will occur, and MS1525 (2019) suggests using shading devices to control direct sunlight. There are several options, such as reflective glass and low-E glass, instead of clear glass, but it is more expensive compared to clear glass. Nevertheless, it is worth it for long time usage. Referring to the PWD Handbook of Passive Design (2010) and BSEEP Passive Design Guidebook (2013), the VLT value should be between 70% and 80% for maximum daylight levels. However, the minimum must not be less than 20% to avoid glare and ensure that the light is distributed evenly. The glazing in Classrooms 1 and 2 was a black tinted film with a VLT of approximately 43% to 48%. On the other hand, Classroom 3 was clear glass with a VLT of approximately 81% to 90%. To simplify, Classrooms 1 and 2 were required to adjust the glazing properties to increase the VLT value.

4.3.4 Sun Shading

Table 13 – Observation Analysis of Sun Shading

	Classroom 1	Classroom 2	Classroom 3
Characteristics	No shading devices inside and outside of the façade.	No shading devices inside and outside of the façade.	No shading devices inside and outside of the façade.
Average indoor illuminance level	162 lux	85 lux	998 lux
Average outdoor illuminance level	37796 lux	41395 lux	44796 lux

Table 13 indicates no shading devices in any of the classrooms, either inside or outside. The outdoor illuminance ranged between 30,000 to 50,000 lux. According to MS1525:2019, with that range of outdoor illuminance, the indoor illuminance must be between 300 to 3,000 lux. The table shows that only Classroom 3 was within that range. However, for pleasant daylighting, the range for indoor illuminance for teaching spaces is suggested to be between 300 to 500 lux. The average indoor illuminance in Table 4.28 shows that all of the classrooms were not within the standard. Hence, the low average indoor illuminance level for Classrooms 1 and 2 show that shading devices are unnecessary if the same glazing is used. While Classroom 3 had a high level of indoor illuminance, it was suggested that shading devices control the amount of daylight entering the classroom. The best practice of sun shading recommended for a building is exterior shading that is frequently found in Malaysia's building, either vertical or horizontal plane that effectively block the direct sunlight. Sun shading devices are used on building depending on the solar orientation of a specific façade (MS1525:2019).

4.3.5 Colour of Reflectance

Table 14 – Observation Analysis of Colour Reflectance

	Classroom 1	Classroom 2	Classroom 3
Ceiling	White cement render LRV: 100%	White cement render LRV: 100%	White asbestos LRV: 100%
Floor	Dark grey cement render LRV: 30% - 10%	Dark grey tiles LRV: 30% - 10%	White tiles LRV: 100%
Wall	White cement render LRV: 100%	White cement render LRV: 100%	White cement render LRV: 100%
Chairs	Grey LRV: 50% - 20%	Grey LRV: 50% - 20%	Dark grey LRV: 30% - 10%
Tables	Grey LRV: 50% - 20%	Grey LRV: 50% - 20%	Grey LRV: 50% - 20%
Others	Whiteboard at the front. LRV: 100%	Whiteboard at the front. LRV: 100%	Whiteboard at the front. LRV: 100%

Table 14 shows that Classroom 3 has a light colour reflectance for the ceiling, wall, and floor, which is a good interior surface design because bright colour surfaces will reflect the lighting and absorb less heat. On the other hand, Classrooms 1 and 2 have darker colour surfaces; as daylight enters the classrooms, they absorb the light, resulting in uneven low daylight. Classroom 3 had the advantage of reflecting more light when daylight penetrates the room. It is because the major surfaces, such as the ceiling, floor, and walls, are white, indicating the LRV is 100%. Concerning Classrooms 1 and 2, it was strongly suggested that the colour of the surfaces, especially the floor, be changed to a bright colour to increase the LRV value.

5. Conclusion

The problems identified are the daylighting design failures at the early construction stage. The daylighting design failures include; (1) poor east or west classroom orientation, (2) double-loaded building with single-sided windows, (3) small glazing area for floor and exterior wall provided, (4) vertical windows shape, leading to light-dark contrasts, (5) low window placement, limiting room depth, (6) inappropriate glazing properties, reducing daylight value, (7) no shading devices provided for even daylight distribution, and (8) surfaces low in light reflectance value to keep classroom light and cool. Classroom 3 is the new educational building, and it is why the classroom has many advantages for dealing with daylighting into the building.

Based on the overall data, it is possible to conclude that there was a daylighting problem in the classroom at the current educational institution, which might be one of the reasons for the institution's rising electricity cost. Because all of the classrooms did not reach a sufficient level of daylight illuminance, they were not intended as passive designs. This occurred because each of the case study classrooms had different designs that change the amount of daylighting that entered the classrooms. The failure of daylighting design at an early stage of construction was discovered to be one of the concerns. In conclusion, daylight in the classroom would perform well if proper strategy and planning were considered early in the design process and effectively maintained as used by building users.

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