# DAYLIGHTING AS A SUSTAINABLE APPROACH FOR HIGH-RISE OFFICE IN TROPICS

**Yaik-Wah Lim[1] and Mohd Hamdan Ahmad[2]**
[1]*Department of Architecture, Faculty of Built Environment, Universiti Teknologi Malaysia.*
[2]*Institute Sultan Iskandar of Urban Habitat and Highrise, Universiti Teknologi Malaysia.*

**Abstract**

A high-rise building has always been categorised as a high-energy-consumption building type due to its dependency on artificial indoor environment. This paper investigates the potential of daylight utilisation in high-rise offices in tropical climate for sustainable development. A survey on 13 existing high-rise offices and field measurement in Johor Bahru, Malaysia was conducted. The result indicated the evidence of underuse of daylight, due to the glare and thermal problem, despite the high external daylight availability. Scaled physical model of a typical high-rise office was constructed and tested under various tropical sky conditions: intermediate sky with direct sunlight patch (DSLP), intermediate sky without DSLP and overcast sky. The finding proved that the effective daylighting depth in tropical sky can be as deep as 3.8 times height of the window from work plane (H). A proper control of the dynamic daylighting using shading device and window glazing was needed for effective use of daylight for energy saving and visual comfort.

*Key words: field measurement, scaled model, shading device, window glazing*

## 1.0 INTRODUCTION

Statistic by United Nation (2001) indicated that the percentage of population living in urban areas increased from 30% in 1950 to 40% in 2000. It is expected to reach 60% by 2030. Urbanisation causes rapid development of high-rise buildings in cities all over the world. The buildings emit large amount of carbon dioxide that constitutes almost half of that which is responsible for greenhouse effect (John *et al*., 2005). Therefore, sustainability in high-rise building design can never be overlooked.

Undeniably, commercial buildings consume high electricity world-wide, as well as in Malaysia (Zain-Ahmed, 2008). The Ninth Malaysia Plan 2006-2010 (RM9) indicated residential and commercial sectors that demand 12.8% of the total energy use in Malaysia by year 2010 (Malaysia, 2006). According to energy audit of ASEAN's buildings (Loewen *et al*., 1992), typical Malaysian office buildings recorded average building energy index (BEI) of 269 kWh/m$^2$/yr, which is higher than the average BEI of 233 kWh/m$^2$/yr in ASEAN generally. The data indicated that air-conditioning consumed 60.1 %, while lighting consumed 23.1% of the electricity use in office buildings.

In a more recent energy audit in Malaysian office buildings conducted by Green Tech Corporation (formally known as Pusat Tenaga Malaysia), the data demonstrated that typical Malaysian office buildings yielded BEI of about 250 kWh/m$^2$/yr. The breakdown of energy consumption is about 64% for air-conditioning, 12% for lighting and 24% for general equipment (Chan, 2009). In conclusion, office buildings in Malaysia recorded high BEI. Air-conditioning is the highest energy consumption component, followed by electric lighting,whereas the BEI between 65 to 135 kWh/m2/yr is achievable as demonstrated by Green Energy Office (GEO) building in Bangi and Low Energy Office (LEO) building in Putrajaya.

With the hot and humid tropical climate in Malaysia, the major drawbacks for sustainability in building design are intensive solar radiation and heat gain. Record from Subang Jaya Meteorological Station, Malaysia showed that the annual maximum levels of intensity of solar radiation falling on horizontal and vertical surfaces are about 1000 W/m$^2$ and 850 W/m$^2$, respectively, for east and west facing surfaces (Ossen, 2005).

Daylighting has been proven as an effective strategy to provide energy saving for electric lighting, as well as visual comfort for users (Dubois 2001a; Zain-Ahmed, 2002a; Carmody *et al*., 2004). In the tropical climate, global illuminance can go as high as 100,000 lux or more. Yet, some researchers (Mohd Hamdan, 1996; Ossen, 2005) concluded that the abundance of daylight in the tropics has not been utilised to the maximum since it is usually concurrent with intense solar heat gain. Therefore, the balance between the prevention of sunlight radiation heat gains and utilisation of natural daylight is very crucial in order to achieve building energy efficiency (Sharifah and Sia, 2004; Tzempelikos and Athienitis, 2007; Lim *et al*., 2008; Lim *et al*., 2009). The aim of this paper is to investigate the potential use of daylight in the contemporary high-rise office buildings as a sustainable approach to energy saving and visual comfort in the tropical climate.

## 2.0 DEVELOPMENT OF CONTEMPORARY HIGH-RISE OFFICE IN MALAYSIA

The Malaysian economy has transformed from a commodity-based to an industrialised and knowledge-based economy. The services sector has become one of the fastest growing sectors in this country. The development of services sub-sectors such as education, health, professional services, transportation, telecommunication, computer industry services, retail trade, etc., has contributed to a GDP increase from 38.3 % in 1978 to 58.2 % in 2005 (Aris, 2007). With the development of services sector, small and medium enterprises (SMEs) have become a vital component of the country's economic development (Saleh and Ndubisi, 2006). [The definition of SMEs by National SME Development Council, based on number of full-time employees, is stated in Table 1.] For the services sector, enterprises with lesser than 5 employees are considered as 'micro'; those having between 5 and 19 employees as 'small'; while those having between 20 and 50 employees 'medium'.

Table 1 Definition of SMEs for different sectors based on number of full-time employees

| Size | Number of Full-time employees | | |
|---|---|---|---|
| | Manufacturing | **Services** | Agriculture |
| Micro | < 5 | **< 5** | < 5 |
| Small | 5 – 50 | **5 – 19** | 5 – 19 |
| Medium | 51 – 150 | **20 – 50** | 20 – 50 |

Table 2 : Distribution of SMEs in general and services sector in Malaysia

| Type | General | | Services Sector | |
|---|---|---|---|---|
| | No. of Establishment in 2000 | Percentage (%) | No. of Companies | Percentage (%) |
| **Micro** | **7,171** | **35.0** | **114,840** | **59.6** |
| **Small** | **9,445** | **46.2** | **53.612** | **27.8** |
| Medium | 1,655 | 8.1 | 17,976 | 9.3 |
| Large | 2,184 | 10.7 | 6,099 | 3.2 |
| Total | 20,455 | 100 | 192,527 | 100 |

According to Department of Statistic Malaysia, micro and small enterprises have the highest number of establishments among all enterprise sizes (Saleh and Ndubisi, 2006). Generally, micro enterprises contribute 35.0% of total enterprises establishments, while small enterprises are 46.2% (Table 2). For services sector, micro enterprises are even more evident. Micro enterprises yield 59.6%; while small enterprises are 27.8% of the total number of companies. This demonstrated that, in Malaysia, 59.6% of enterprises in services sector have an employment size below 5 persons, while 87.4% abelow 20 persons.

Since the majority of tenants of the high-rise offices belonged to services sector, rationalisation can be made that the majority of these companies need a small office space with the number of users below 20 people. Many of these companies even have the number of users below 5people. Thus, open plan space is one of the typical layouts for high-rise offices. This kind of office comprises many individual workstations which are in visual and acoustical contact with each other. The first open plan office was developed in the 1960s and was called as office landscape. This office planning rejects the rigid grid systems and does not include any private offices (Reinhart, 2002). However, it is more challenging to control an open plan office environment for users' comfort and satisfaction due to various individual preferences for lighting, acoustic and privacy (Yildirim *et al*., 2007).

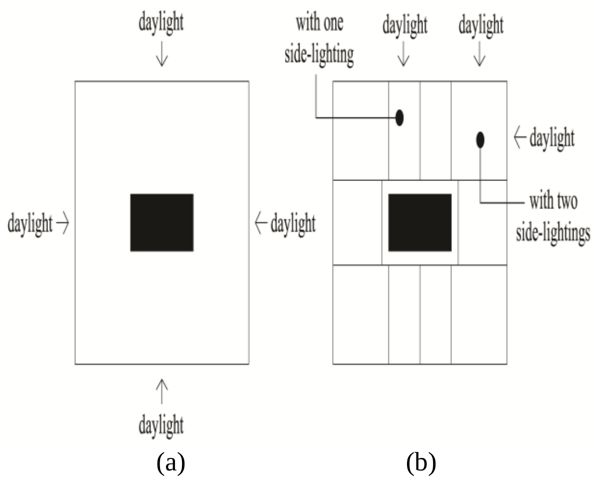


Fig. 1 Contemporary high-rise floor plan showing (a) open plan office with good daylighting from all sides; (b) small rentable open plan offices with limited daylighting after partitioning (Lim, 2011).

The use of daylight in open plan office shall be optimised as there is no full height partition. A good open plan office design shall harvest the daylight from different sides of the external walls to create a spacious working environment (as shown in Figure 1a). However, in many current high-rise offices, the rentable floors are actually divided into smaller units for different tenants because many of them do not require a large office space. Thus, the access to daylight is limited by only one side-lighting except for the corner units (Figure 1b). Some of the tenants even partition the office units for individual room and open plan office purposes. Therefore, the use of daylight in this kind of open plan offices is very limited and demanding critical improvement.

## 3.0 HIGH-RISE OFFICE LUMINOUS ENVIRONMENT

Luminous environment is very important to provide comfortable and healthy office environment to the users. Especially in high-rise offices, users are working inside a huge internal environment, lack of exposure to the external. Individual cellular offices provide more controllable lighting environment to the users. Since most of these offices only have 1 or 2 users, they can adjust the lighting setting according to their preferences, such as tilting the blinds, switching off electric light, etc. The more challenging spaces are the open plan offices, where more users are working in the same space (Reinhart, 2002; Yildirim *et al*., 2007). As human response to light is very subjective, each user may have different preferences for visual comfort (Ander, 2003). In a critical environment like this, conflicts may occur among the users. Besides, in many cases, no user is responsible or concern to adjust the electric lighting or blinds (Reinhart and Voss, 2003). Thus, some of them choose to close up all the windows with blinds and totally rely on electric lighting which is more consistent and controllable.

High-rise offices have the advantage of utilizing daylighting because these offices are not blocked by adjacent vegetation or buildings (except in high dense city). Nevertheless, high-rise offices also have larger vertical façade exposed to direct solar radiation (Chia, 2007). When the sun is at a low angle, direct sunlight penetrates into the offices. Thus, proper façade treatment and internal shading are very important to eliminate direct sunlight and control daylight distribution. Especially when most of the users nowadays are performing computer tasks using VDT, glare problem is very sensitive (Dubois, 2001b).

In Malaysia, since many tenants in high-rise offices belong to SMEs, the number of users is below 20 persons. In this kind of small open plan office, it is infeasible to install high cost daylighting system such as light pipe and automatic control systems. Thus, passive daylighting strategies are needed to achieve daylight efficiency such as using blinds, light shelves, reflective ceiling, etc.

A case study on luminous condition in 13 high-rise open plan offices in the city centre of Johor Bahru was once conducted (Lim and Mohd Hamdan, 2010). The case study covered 72.22 % of the total available high-rise office buildings in the city centre of Johor Bahru (as shown in Figure 2). The case study was carried out from 8 January 2010 until 1 February 2010. All the visits were done during common office working hours from 9.00 hr to 17.00 hr. Physical measurements were conducted using Light Meter LX-100 (range 0-20000 lux) for indoor work plane illuminance (WPI) and Luminance Meter Topcon BM9 for the surface luminance. A total of 33 sets of questionnaire were distributed among the users of the 13 study cases to evaluate the visual comfort of their current offices. Generally, the response from the users was not so encouraging because the overall percentage of respondents was only 54.2%.


Fig. 2 Google Earth view indicating the locations of the identified high-rise office buildings in Johor Bahru city centre (Lim and Mohd Hamdan, 2010).

The findings of the case study highlighted the following issues in high-rise open plan offices (Lim and Mohd Hamdan, 2010):

1. Extensive use of internal shading that totally covers the window from daylight penetration regardless of orientation causes unhealthy working environment and high dependency on electric lighting. Besides, due to the use of internal shading, the absence of external view through the window creates boring working environment. According to the questionnaire results, the office users desire view of natural surroundings such as greenery and sky. Nevertheless, it is very difficult for high-rise offices to have greenery view as they are located high above the ground. Design of planter box, balcony and sky garden can be pragmatic solutions to provide greenery as well as sky view. These kinds of features can be observed in some of the bioclimatic high-rise designs by Yeang (1994).

2. Monotonous electric lighting using fluorescent lights throughout the offices gives dull working environment that will lead to tiredness and unproductiveness among the users. However, users tend to be adapted to the existing lighting levels that they feel satisfied although the electric lighting level is actually below the minimum requirement or the luminance contrast is too high.

3. There is lack of awareness of daylight utilisation among the office users. Electric lightings were on almost throughout all the working days. They seldom switch off the electric lights even when daylight is sufficient, and do not consider daylighting for workspaces arrangement. Users tend to cover up the windows with internal shading (Figure 3). The findings have proven that office users are ignoring the possible use of daylight.

4. Internal shading device is the most significant design criteria that determine the daylight penetration. Controlling the daylight penetration is the most important factor for improving WPI uniformity and reducing luminance contrast. Subsequently, other design criteria such as surface reflectance are actually further enhancing the lighting performance. Besides, internal shading also determines the availability of external view.

5. There is an urgent demand of efficient daylight design recommendation for high-rise open plan offices towards visual comfort and energy saving.

Fig. 3 Examples of high-rise office study cases in Johor Bahru with external windows covered by internal shadings (Lim, 2011).

## 4.0 TROPICAL SKY CONDITION

Previous studies have employed various methods to predict the tropical sky condition. By using cloud cover ratio, Rahim and Mulyadi (2004) suggested the sky condition in Makassar,

Indonesia as 15.32% clear sky, 69.80% intermediate sky, and 14.88% overcast sky. According to Zain-Ahmed *et al*. (2002b), the monthly average nebulosity index (NI) of the sky at Subang, West Malaysia indicates that 85.6% of the time the sky was predominantly intermediate, 14.0% overcast and 0% blue. Besides, the average NI for Malaysian sky was 0.52, within the range of intermediate mean (0.20 – 0.70). Djamila *et al*. (2011) further studied the sky condition at Kota Kinabalu, East Malaysia using both NI and sky ratio. The results disclosed that 70 - 90% of the sky was intermediate using cloud cover ratio; 100% of the sky was predominantly intermediate for the whole year using NI method. All of the previous studies concluded that tropical sky is predominantly intermediate, which is neither clear nor overcast.

Though there is no long term measurement, daylighting models had been employed to predict the global illuminance in hot humid tropic. Many of these models calculate the luminous efficacy using irradiance data. Zain-Ahmed *et al*. (2002b) employed the General Exterior Illuminance Prediction Model to model the exterior daylight data for Malaysia. The Du Mortier-Perraudeau-Page (DPP) model was used for all sky types to estimate the global luminous efficacy. The Munner's recommended value for beam luminous efficacy, $K_B$ = 104 lm/W were applied. The calculated annual average values of diffused luminous efficacy, $K_D$ and global luminous efficacy, $K_G$ for Subang, Malaysia area were 120 lm/W and 112 lm/W respectively. These values were between the established values for overcast (115 lm/W) and clear skies (144 lm/W). The calculated external illuminance, $E_G$ exceeded 80,000 lux at noon during March when solar irradiation was highest; and reached 60,000 lux even during December, when the ground received less solar radiation.

During office working hours (9-17 hr), the $E_G$ mostly exceeded 20,000 lux.

Zain-Ahmed *et al*. (2002b) also further compared the calculated results with field measurement. The mean $K_G$ based on measurement in Shah Alam and Bangi, M Page 5 indicated 119+2% lm/W and 133+2% respectively. From the field measurements, it was found that the $E_G$ values could exceed 100,000 lux at Shah Alam, Malaysia and 140,000 lux at Bangi, Malaysia. The similar methodology was employed again by Zain-Ahmed *et al*. (2007). In this experiment, instead of measuring the illuminance, sky scanner was used to measure the sky luminance, L (cd/m$^2$ = lm.sd-1.m$^{-2}$). The results indicated $K_G$ = 106 lm/W and $K_G$ = 112 lm/W respectively. The authors concluded that $K_G$ = 112 lm/W is more representative of the normal tropical sky condition in Malaysia. This value is exactly the same as calculated $K_G$ from DPP model.

DOE (Department of Energy, United States) weather files for Kuala Lumpur, West Malaysia was studied to calculate the $K_G$ (Ossen, 2005). The results indicated a value of 118 lm/W, which is very close to the established value by measured data at Shah Alam (119+2% lm/W). Malaysian tropical daylight availability was further investigated by Djamila *et al*. (2011) at Kota Kinabalu, East Malaysia by using Perez daylight model. The results were compared with DPP model, showing that DPP model tends to underestimate the diffuse illuminance, $E_d$. Hence, Perez model is more suitable to predict $E_G$ under Malaysian sky. Besides, $K_b$ higher than the average recommendation, 126 lm/W produced almost identical $E_G$. The authors suggested that Munner's $K_b$ = 104 lm/W might be more suitable under temperate sky conditions, not the tropical sky.

The global and diffused vertical illuminance at Kota Kinabalu, East Malaysia was predicted using Prerez model (Djamila *et al*., 2011). The findings showed that the window oriented east receives highest illumination on 21 March. Because the sun is behind the north façade during the two equinoxes, south surface receives more illumination than the northern surface. Diffused illuminance, $E_d$ is the main source of daylighting for the north and south facing windows. While for east facing windows, the $E_d$ is the only source of daylighting from noon till sunset. The situation is reversed for west facing windows.

## 5.0 FIELD MEASUREMENT IN JOHOR BAHRU

To further investigate the tropical external daylight availability, $E_G$ was measured at Johor Bahru, West Malaysia from 26 March 2011 until 6 May 2011 (6 weeks). Illuminance meter Delta OHM LP-PHOT 02 with data logger was employed to measure the $E_G$ with intervals of 10 minutes. The measurement range of the equipment was 0 – 150 klux. An example of the data collected is shown in Figure 4 (for week 1). Generally, the $E_G$ was high throughout the measurement period. The highest recorded $E_G$ was about 140,000 lux at 1230hr.

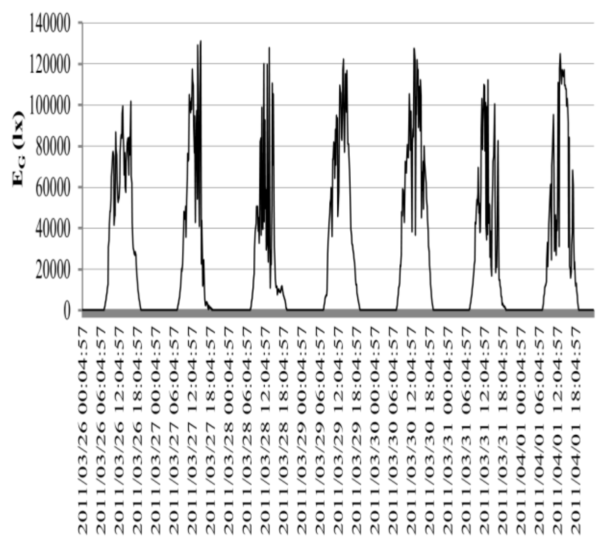


Fig. 4 $E_G$ (lux) from 26 March 2011 to 1 April 2011 (week 1).

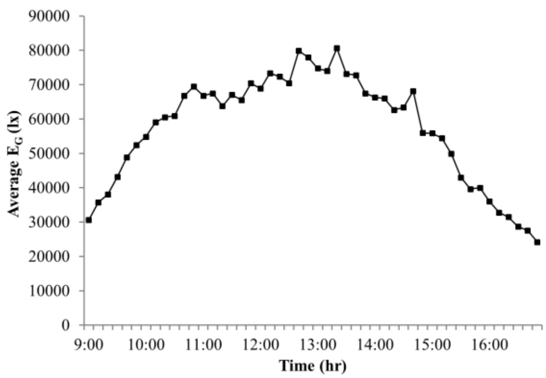


Fig. 5 Average $E_G$ (lux) during office hour (9-17hr) from 26 March 2011 to 6 May 2011.

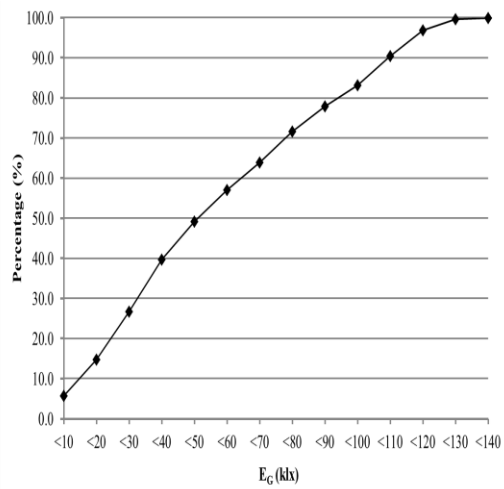


Fig. 6 Percentage of hours during office hour (9-17hr) recorded below a given $E_G$ (klux).

Further analysis was carried out by computing the average $E_G$ during office working hour (9-17hr) as shown in Figure 5. The result indicates that the average $E_G$ throughout the 6 weeks was always higher than 20,000 lux, with the peak of 80,000 lux at about 1pm. This finding corresponds with the previous research (Zain-Ahmed *et al*., 2002b; Djamila *et al*., 2011). Percentages of hour during office working hour recorded below a given value of $E_G$ were plotted in Figure 6. The result shows that less than 6% of the time yielded $E_G$ below 10,000 lux. Most of the time during office working hour (85.2%), the $E_G$ was higher than 20,000 lux. Furthermore, 50% of the time recorded $E_G$ higher than 50,000 lux.

## 6.0 SCALED PHYSICAL MODEL EXPERIMENT

Two scaled physical models of typical high-rise office were constructed to test the daylight penetration pattern under various tropical sky conditions. The configurations of the models are shown in Figure 7 with a scale of 1:20. These models represent an open plan office within the typical 8.4 m x 8.4 m structural grid. The external window sill height was the same as the work plane height (800 mm) because daylight penetration below the work plane height will not affect the work plane illuminance (WPI). These models have a full opening without glazing above the work plane which result in window-to-wall ratio (WWR) of 70.4 %. The model internal surface reflectance values are stated in Table 3.

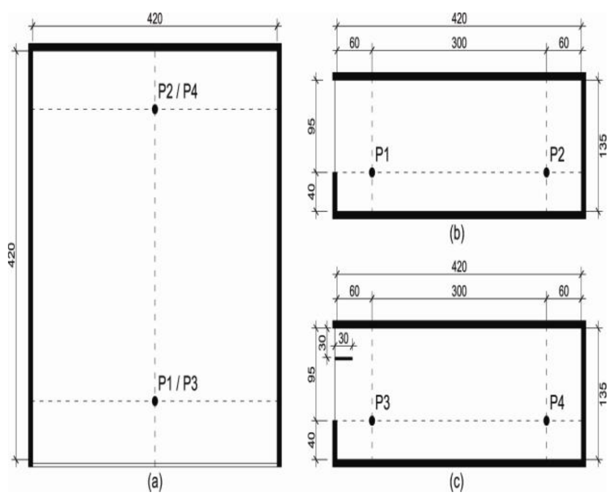


Fig. 7 Configuration of the physical model with scale 1:20: (a) Plan; (b) Section of Base Case; (c) Section with Light Shelf.

Table 3 : Internal surface reflectance

| Surface | Reflectance Value |
|---|---|
| Wall | 57.26% |
| Ceiling | 61.73% |
| Floor | 16.78% |
| Light Shelf | 51.29% |

Fig. 8 Daylight measurement using Delta OHM LP-PHOT 01 with data loggers for internal illuminance and Delta OHM LP-PHOT 02 with data logger for external illuminance.

As shown in Figure 8, 2 the models were tested concurrently in this experiment: (1) Base Case model and (2) Model with internal Light Shelf (LS). The Base Case model was used as a reference to compare the performance of the model with internal LS. One illuminance meter Delta OHM LP-PHOT 02, Probe E (PE) with data logger was installed on the top of the models to measure the external illuminance. The measurement range of the equipment was 0 – 150 klux. Concurrently, 4 illuminance meters Delta OHM LP-PHOT 01 with data loggers, Probe 1 (P1) and Probe 2 (P2) were installed inside the Base Case model; while Probe 3 (P3) and Probe 4 (P4) were installed inside the model with internal LS, to measure internal WPI. P1 and P3 were located 60 mm from the external window, while P2 and P4 were situated 60 mm from the rear wall, at the work plane height (80 mm).

Table 4 : Summary of measurements

| **Date** | **Time** | **Orientation** | **Sky Condition** | **DSLP** |
|---|---|---|---|---|
| 6 March 2012 | 1215 - 1230 hr | North | Intermediate | X |
| 7 March 2012 | 0915 - 0930 hr | East | Intermediate | √ |
| 8 March 2012 | 1500 - 1515 hr | West | Intermediate | √ |
| 9 March 2012 | 1145 - 1200 hr | South | Overcast | X |

All the measurements were taken during 6 - 9 March 2012, with intervals of 30 seconds. During the measurement, the sky conditions and availability of direct sunlight patches (DSLP) were observed. All the measurements taken are summarised in Table 4. The data collected were then analysed to study the absolute WPI level and WPI uniformity ratio (Equation 1) for various sky conditions and orientations. WPI for different glazing types was experimented by multiplying the recorded data with respective visible transmittance (VT) as shown in Equation 2. In this experiment, 3 types of glazing were tested: (1) clear glazing with VT 0.75; (2) tinted glazing with VT 0.50; and (3) reflective glazing with VT 0.25.

$$\text{WPI Uniformity Ratio} = \text{Minimum WPI } (E_{min}) / \text{Average WPI } (E_{avg}) \quad (1)$$

$$\text{WPI}_{\text{with glazing}} = \text{WPI}_{\text{without glazing}} \times \text{VT}_{\text{selected glazing}} \quad (2)$$

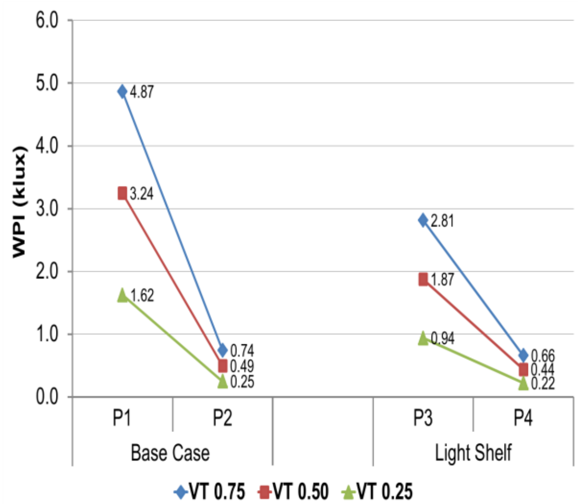


Fig. 9 WPI (klux) during intermediate sky without direct sunlight patch on North (Noon).

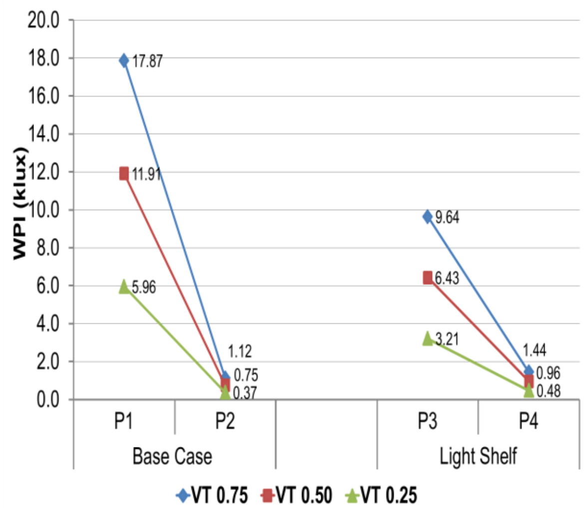


Fig. 10 WPI (klux) during intermediate sky with direct sunlight patch on East (Morning).

Figure 9 shows that P1 was constantly higher than P2 while P3 was always higher than P4. This demonstrated the diminishing effect of daylight penetration for both Base Case and Model with Internal LS. The results recorded that P1 with clear glazing, tinted glazing and reflective glazing yielded WPI as high as 4,870 lux, 3,240 lux and 1,620 lux respectively. This shows that area near to external window received extremely high WPI which will cause thermal and glare problem. Meanwhile, even P2 (near to rear wall) with reflective glazing (VT 0.25) was still able to achieve WPI of 250 lux. This indicates that Base Case without LS under intermediate sky received extremely high daylight level even with tinted glazing. When internal LS was installed, P3 recorded lower WPI with 2,810 lux, 1,870 lux and 940 lux for clear, tinted and reflective glazing respectively. However, P4 was still able to achieve WPI slightly lower than P2 (Base Case). This helps to increase the daylight distribution uniformity.

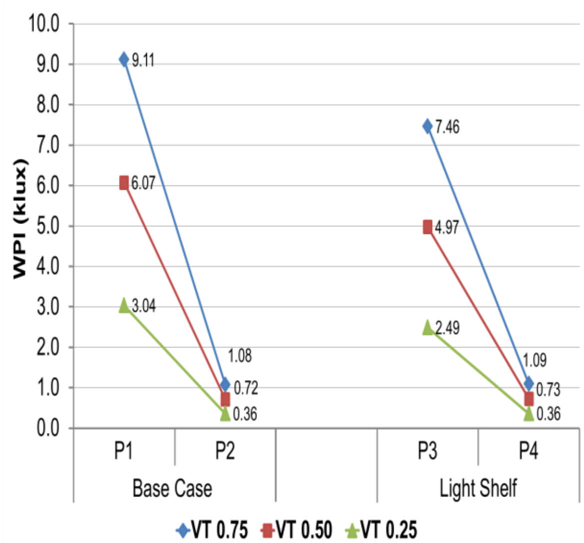


Fig. 11 WPI (klux) during intermediate sky with direct sunlight patch on West (Afternoon).

Figures 10 and 11 show the WPI recorded during intermediate sky with DSLP on the East (morning) and West (afternoon) orientations. The results show that with the presence of DSLP, the WPI levels were much higher. The highest recorded WPI was 17,870 lux for East orientation and 9,110 lux for West orientation, at P1 with clear glazing. Even at the area near to the rear wall (P2), the lowest WPI was still able to achieve the MS1525 minimum recommendation of 300 lux for general office (Department of Standards Malaysia, 2007). The results demonstrates that under intermediate sky with DSLP, the daylight level was extremely high especially for clear glazing, where P2 was still higher than 1,000 lux.

The use of LS for intermediate sky with DSLP was able to reduce the extremely high WPI at P3 and to increase the WPI at P4 in comparison with P2. Especially on the East orientation, the LS has increased the WPI at the area near the rear wall significantly in comparison with the Base Case. This shows that LS was more effective to increase daylight distribution uniformity with the presence of DSLP under intermediate sky.

The results demonstrate that internal WPI near to external window was still considerably high even under overcast sky in tropical climate. Figure 12 shows that P1 yielded WPI of 4,170 lux, 2,780 lux and 1,390 lux with clear, tinted and reflective glazing, respectively. However, at the area near to the rear wall, only clear glazing was able to achieve WPI above 300 lux. With the use of LS, P3 was reduced significantly while P4 remained similar with P2. This indicates that LS under overcast sky was effective to increase the WPI uniformity.

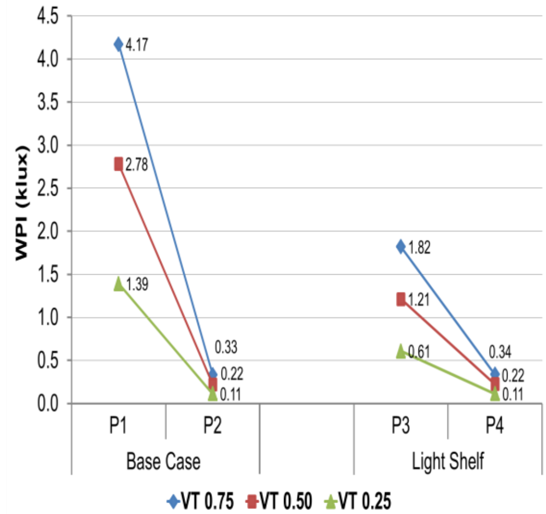


Fig. 12 WPI (klux) during overcast sky.

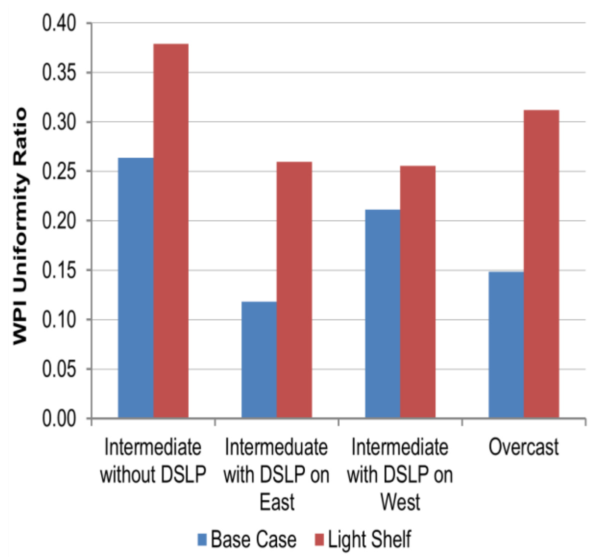


Fig. 13 WPI uniformity ratio for Base Case and Light Shelf.

Figure 13 compares the WPI distribution uniformity ratios between the Base Case and Model with internal LS under various sky conditions. The result shows that the LS was able to increase the uniformity as much as 43.66%, 119.91%, 20.85% and 110.55% for intermediate sky without DSLP, intermediate sky with DSLP on East, intermediate sky with DLSP on thWest and overcast sky, respectively.

## 7.0 DISCUSSION

Previous research showed that most of the existing high-rise offices in Malaysia had ignored daylight and totally relied on the electric lights alone (Lim and Mohd Hamdan, 2010). One of the main reasons of this phenomenon is the excessively high and unpredictable global illuminance in the tropical climate. Global illuminance may vary drastically within a few minutes due to the formation of clouds (Mohd Hamdan, 1996). Thus, it is challenging to control the glare and uniformity of indoor daylight distribution under the tropical sky.

The field measurement of external illuminance at Johor Bahru proved that the Malaysian tropical sky is predominantly intermediate, with high daylight availability that can easily exceed 50,000 lux. Therefore, the challenge of tropical daylighting design is not to assure sufficient quantity of daylight penetration, but is to control the quality of the daylight distribution. This is very critical to provide visual comfortable working environment. $E_G$ of 20,000 lux shall be employed for tropical daylight factor analysis in office building. Nonetheless, daylighting for other purposes such as residential buildings which require varied occupancy times demands further investigation.

The findings of the scaled model experiment indicated that various sky conditions gave various daylight penetration patterns. In overall, all the sky conditions gave extremely high WPI (> 1,000 lux) at the area near to external window even with low VT reflective glazing. Intermediate sky recorded higher WPI in comparison with overcast sky. Moreover, intermediate sky with DSLP yielded the highest WPI. The experiment evidenced that the Base Case design without any shading device, which is the common design in the contemporary high-rise offices, will result critical glare and thermal problems due to the excessively high WPI.

Previous research by Shahriar and Mohit (2007) in a tropical climate stated that the depth of daylighting zone for 300 lux WPI was 3.5 m. This paper demonstrated that the effective daylighting depth (> 300 lux) in tropical sky can be as deep as 7.2 m even under overcast sky with clear glazing (VT 0.75). Although the commonly used daylighting rule of thumb suggests that the depth of daylight area is 2.5 times height of the window from work plane (2.5 H), this study proved that the depth of daylight area in a tropical climate can be as much as 3.8 H.

In general, LS has successfully improved the daylight uniformity while still allowing sufficient daylight level for electric lighting energy saving and visual comfort. The use of LS has yielded different performances for difference sky conditions. The findings showed that LS was most effective during overcast day and intermediate day with DSLP on the East orientation. This finding suggested that the design of LS shall respond to that orientation. A dynamic control of the LS is needed as sky conditions change dynamically.

## 8.0 CONCLUSION

This paper concludes that there is abundance of daylight available in the tropical climate that can be applied as a sustainable design approach for contemporary high-rise offices. However, the drawback of utilising tropical daylighting is excessively high daylight level which will result in glare problem at workplace. Especially in open plan office, occupants have to adjust their working area’s position to achieve visual comfortable settings. Apart from that, the daylighting performances for different orientations and sky conditions vary significantly. The presence of DSLP determines the effectiveness of light shelf. Thus, the design of light shelf shall be flexible or adjustable to respond to the various sky conditions in the tropical climate.

**ACKNOWLEDGEMENT**

The authors would like to acknowledge the research funding by Universiti Teknologi Malaysia (UTM), Ministry of Higher Education (MOHE) through Research University Grant (GUP), Vote 02H14, titled "Smart Shading Device for Building Energy Saving in the Tropics".

**References**

Ander, G. D. (2003). *Daylighting Performance and Design*. New Jersey: John Wiley & Sons, Inc.

Aris, N. M. (2007). SMEs: Building Blocks for Economic Growth. *Journal of the Department of Statistics*, Malaysia, 1: 1-13.

Carmody, J., Selkowitz, S., Lee, S. E., Arasteh, D. and Willmert, T. (2004). *Window Systems for High Performance Buildings*. (1st ed.) New York: W.W.Norton & Company, Inc.

Chan, S. A. (2009). Green Building Index - MS1525. *PAM CPD Seminar: Applying MS1525:2007 Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings*. 14 February. Kuala Lumpur, Malaysia, 1-22.

Chia, S. L. (2007). *Minimizing solar insolation in high-rise buildings through self-shaded form*. Master of Architecture, Faculty of Built Environment, Universiti Teknologi Malaysia.

Department of Standards Malaysia (2007). MS 1525: 2007. *Malaysian Standard: Code of Practice on Energy efficiency and Use of Renewable Energy for Non-Residential Buildings* (1st Revision). Malaysia.

Djamila, H., Ming, C. C. and Kumaresan, S. (2011). Estimation of exterior vertical daylight for the humid tropic of Kota Kinabalu city in East Malaysia. *Renewable Energy*, 36:9-15.

Dubois, M. C. (2001a). *Impact of Solar Shading Devices on Daylight Quality: Measurements in Experimental Office Rooms*. Research Report. Lund, Sweden: Lund University.

Dubois, M. C. (2001b). *Impact of Solar Shading Devices on Daylight Quality: Simulations with Radiance. Research Report*. Lund, Sweden: Lund University.

John, G., Clement-Croome, D. and Jeronimidis, G. (2005) Sustainable building solutions: a review of lessons from the natural world. *Building and Environment*, 40 (2005): 319–328.

Lim, Y. W. and Mohd Hamdan, A. (2010). Daylight and Users' Response in High Rise Open Plan Office: A case study of Malaysia. *3rd. International Graduate Conference on Engineering, Science, and Humanities*. 2-4 November.

Lim, Y. W., Mohd Hamdan, A. and Ossen, D. R. (2008). Review on measuring tools for energy efficient solar shading strategies in tropical climate. *Jurnal Alam Bina*, 14(5): 33-42.

Lim, Y. W., Mohd Hamdan, A. and Ossen, D. R. (2009). Effect of solar shading, fenestration and room geometry on office building energy efficiency in hot humid tropic. *3rd. International Conference on Built Environment in Developing Countries*. 2-3 December. Universiti Sains Malaysia, USM, Penang, Malaysia, 174-185.

Lim, Y.W. (2011). *Internal Shading for Efficient Tropical Daylighting in High-rise Open Plan Office. Doctor of Philosophy*, Faculty of Built Environment, Universiti Teknologi Malaysia.

Loewen, J.M; Levine, M.D and Busch, J.F (1992). *ASEAN-USAID Building Energy Conservation project: Final Report-Audit*. Vol. III. Berkeley, Lawrence Berkeley Laboratory, University of California.

Malaysia (2006). *The Ninth Malaysia Plan 2006-2010.* Kuala Lumpur: Government publication.

Mohd Hamdan, A. (1996). *The Influence of Roof Form and Interior Cross Section on Daylighting* *in the Atrium Spaces in Malaysia*. Doctor of Philosophy, University of Manchester.

Ossen, D.R. (2005). *Optimum Overhang Geometry for High Rise Office Building Energy Saving in Tropical Climates*. Doctor of Philosophy, Faculty of Built Environment, Universiti Teknologi Malaysia.

Rahim, R. and Mulyadi, R. (2004). Preliminary study of horizontal illuminance in Indonesia. *5th SENVAR*. December. Universiti Teknologi Malaysia.

Reinhart, C. F. and Voss, K. (2003). Monitoring manual control of electric lighting and blinds. *Lighting Research and Technology*, 35(3): 243–260.

Reinhart, C.F. (2002). Effects of interior design on the daylight availability in open plan offices. *Conference Proceedings of the ACEEE Summer Study on Energy Efficient Buildings*. August. Pacific Grove, CA., U.S.A., 1-12.

Saleh, A. S. and Ndubisi, N. O. (2006). An Evaluation of SME Development in Malaysia. International *Review of Business Research Papers*, 2(1): 1-14.

Sharifah, F.S.F and Sia, S.J (2004). Sunlight control and daylight distribution analysis: The KOMTAR case study. *Building and Environment*, 39: 713-717.

Tzempelikos, A. and Athienitis, A.K. (2007). The impact of shading design and control on building cooling and lighting demand. *Solar Energy*, 81: 369-382. doi:10.1016/j.solener.2006.06.015

United Nation (2001). *World population monitoring 2001*. New York: UN, Department of Economic and Social Affairs, Population Division.

Yeang, Ken. (1994). *Bioclimatic Skyscrapers*. London: Artemis London Limited.

Yildirim, K., Akalin-Baskaya, A. and Celebi, M (2007). The effects of window proximity, partition height, and gender on perceptions of open-plan offices. *Journal of Environmental Psychology*,27: 154–165.

Zain-Ahmed, A. (2008). Renewable Energy, Buildings and the Fuel Crisis. *International Conference on Construction and Building Technology*. 16 - 20 June . Grand Seasons Hotel, Kuala Lumpur, 13-24.

Zain-Ahmed, A., Omar, H., Alwi, M. Y., Osmar, M. and Ahmed, S. (2007) Estimation of outdoor illuminance for passive solar architecture in Malaysia. *2nd PALENC Conference and 28th AIVC Conference on Building Low Energy Cooling and Advanced Ventilation Technologies*. September. Crete Island, Greece, 1163-1166.

Zain-Ahmed, A., Sopian, K, Othman, M.Y.H and Abidin, Z. Z. (2002b). The Availability of Daylight from Tropical Skies: A Case Study of Malaysia. *Renewable Energy*, 25: 21-30.

Zain-Ahmed, A., Sopian, K, Othman, M.Y.H, Sayigh, A.A.M and Surendran, P.N. (2002a). Daylighting as a passive solar design strategy in tropical buildings: A case study of Malaysia. *Energy Conversion and Management*, 43:1725-1736.