Optimum Overhang Geometry for Building Energy Saving in Tropical Climates

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Abstract

In hot and humid climates, one draw back of using shading devices is the risk of reducing daylight level which in turn increases the use of artificial lighting. It is important to understand the magnitude of energy consumption for cooling and lighting when shading devices are adapted in order to propose optimum external horizontal shading strategies as design solutions. This study investigates the effect of six different alternatives of external horizontal shading devices on incident solar radiation, transmitted solar heat gains, natural-light penetration and energy consumption. The study was carried out using a standard, single fenestration perimeter office room in a typical high-rise office building. The investigation is conducted using eQUEST-3, which is a dynamic energy simulation program supported by DOE2.2 calculation engine. The results showed several optimum geometry of the external horizontal shading device depending on incident direct solar radiation, transmitted solar heat gains, natural-light penetration and energy consumption. This study concludes, considering the trade off between total heat gain and natural-light penetration to optimize the total energy consumption as the best option in designing external solar shading in hot and humid climates.

Keywords: tropical climate; overhang; incident solar radiation; natural light; energy consumption

1. Introduction

The intensity of solar radiation in hot humid climates such as Malaysia is generally high and uniform throughout the year. Records of hourly solar radiation data for Altitude 3.7 North and Latitude 101.3 East (Subang Jaya Meteorological Station), received a maximum of 1055 W/m² for the year 2001. This is about 75-80% of the solar radiation intensity outside the earth’s atmosphere. Further, annual maximum intensity of solar radiation falling on horizontal and vertical surfaces were about 1000 W/m² and 850 W/m² for east and west orientated surfaces.

Energy studies of commercial buildings in south-east Asia, comprising Malaysia, Indonesia, The Philippines, Singapore and Thailand, were initiated under the ASEAN-USAID building energy conservation project in 1992 (Loewen, J.M et al 1992). In Malaysia, buildings are subject to significant cooling requirements due to the high intensity of solar radiation penetration through fenestration. Energy audits and surveys of office buildings for Malaysia indicated that the energy consumed to cool the building is about 55-65% and electric lighting is about 23% of total electricity used (Loewen, J.M et al 1992). The review also showed office buildings in this region have an annual electricity consumption of 838.8 MJ/m²/yr (233 kWh/m²/yr) on average. Comparison among the five countries reveals that Malaysia has the highest electricity consumption of 968.4 MJ/m²/yr (269 kWh/m²/yr) among the office buildings sampled.

In hot and humid climates, although solar radiation prevention is the crucial factor, one draw back of using shading devices is the risk of reducing the natural-light level (direct sunlight & daylight) and as a consequence increasing the use of artificial lighting. What makes natural-light utilization so interesting is that in terms of building energy use it reduces the electricity consumption for lighting and indirectly reduces the cooling demand through reduction of internal heat load from lights. However, the abundance of natural-light in the tropics has not been utilized to the maximum, nor has it been considered as a design criterion (Ahmad, 1996). The main drawback is that maximum natural-light availability is usually concurrent with solar heat gain. The problem is emphasized by the fact that it is important to understand the magnitude of solar heat gain, natural-light penetration and high energy consumption in high-rise office buildings, especially in hot and humid climates like Malaysia.

In broad terms, shading strategies can be categorized into three; natural shading (trees & self shading based on orientation), external shading devices (horizontal, vertical & egg-crate) and internal shading devices (Venetian blinds & roller screens). Previous studies on solar shading have focused mainly on five issues: impact on solar radiation (Hassan KAKU,
1996), daylight quantity and distribution (Sharifah and Sia, 2004; Dubois, 2001) impact on energy use (Dubois, 1999; Raessi and Taheri, 1998; Huang et al 1992) shading design methods (Dubois, 2000) and impact on human comfort and perception (Büow-Hüe, 2000). However, there is room for further research on the relationship between external shading device geometry and on the electric consumption for cooling and lighting. Further, they do not indicate an optimal shading strategy for any particular climate. This paper attempts to elucidate these complex relationships and propose optimum external horizontal shading device strategies as design solutions in hot and humid tropical climates.

One way to take into consideration both cooling load and natural-light utilization in the design of shading devices is to study their impact on energy use and natural-light levels using an energy simulation program (Balcomb 1998). The advantage of using a dynamic energy simulation is that most complex thermal and radiative processes between the building, shading device and the external environment are considered in the calculations. Based on the above assumptions the analysis was carried out using the eQUEST-3 (DOE 2.2) energy simulation program.

3. Methodology
The study is carried out using computer simulation. The sequence of the simulation approach, from the selected program, acquiring required data, construction of model and analysis criteria are discussed below.

3.1. Energy Simulation Program
The simulation “engine” within eQUEST-3 is derived from the latest official version of DOE-2.2, which is an extension of the previous version of DOE-2. Developments and updates of the DOE-2 program have continued since the first version. Since its first release in the late 1970’s DOE-2 has been widely reviewed and validated in the public domain (Sullivan, 1998). Further, Lunneberg and Shank (2003) and Brown et al (2003) reported that eQUEST-3 software was proven reliable and validated for evaluation of energy efficiency measures of typical building forms.

3.2. Preparation of Models
Energy performance of high-rise buildings is influenced by several design variables. The best option to optimize the total building energy consumption is to test the number of design alternatives, which is a time consuming and laborious approach. The other way of dealing with the problem is by varying one variable at a time and keeping the others fixed at reasonable practical values in order to determine the effect of the particular variable on the energy performance of the building.

A single glazing perimeter zone primary unit office room was selected for the simulation. The geometry and characteristics of the typical office room model was developed based on the analysis of high-rise office buildings in Malaysia. The site terrain for the office room was assumed as exposed. This is to minimize the effects of adjacent buildings on the internal lighting and thermal loads of the office room. The geometrical configuration of a base-case office room for the present study was taken as; floor to ceiling height to be 2.8m and width and depth of the room as 6m (Fig.1.). These measurements were taken in order to comply with the gross internal area (GIA) of 36m², while the ratio between height, width and depth, is almost 1:2:2.

Fig.1. Office Room with Overhang Design

In this study, the maximum limit of the window area was assumed as 50 percent (50%) of the net external wall area between the floor and ceiling height. The aperture above the height of the work plane was assumed to be effective in distributing natural-light, while the area below the window sill has no effect on light distribution on the work plane. Therefore the window sill height and the work plane height were assumed to be equal. The window extends from one side of the wall to the other and upward to the ceiling line. Hence, the size of the window is 1.82m in height (above the sill up to ceiling line) and 4.4m in width.

The external overhang is the primary independent
variable in this study. The geometry of the external horizontal shading device depends on three dimensions namely: depth, width and the angle of the shading device (Jorge, et al. 1993). Each of these parameters depends on the amount of solar radiation incident on the fenestration, angle of incident, how much shade is required on the fenestration and also on the size of the fenestration. The depth of the overhang was considered as the main variable in this study. The depth of the device is often described as a dimensionless proportional relationship to the fenestration height.

\[
\text{Overhang} = \frac{\text{Overhang Depth (D)}}{\text{Fenestration Height (H)}}
\]

(from sill to top plate), which is defined as ‘overhang ratio’ (OHR) or ‘projection factor’ (PF).

A range of overhang depths were selected to determine which of the shading hypothesis was optimum in terms of terminating maximum solar heat gain from direct solar radiation. The critical over-heated period during the daytime was considered to be from 9.00 am to 5.00 pm in order to determine the overhang depths. The overhang was extended on either side of the window. Therefore solar radiation and natural-light entering from the side of the window was neglected. Table 1. presents the tested cases of the study and their overhang depths with a relative overhang ratio (OHR).

| OHR = D/H | Overhang Depth |
|-----------|----------------|
|           | In Meters | In Feet |
| 0 (Base Case) | 0         | 0       |
| 0.4       | 0.73      | 2.4     |
| 0.6       | 1.09      | 3.6     |
| 0.8       | 1.46      | 4.8     |
| 1         | 1.82      | 6       |
| 1.4       | 2.55      | 8.4     |
| 1.6       | 2.92      | 9.6     |

The building external wall construction was taken as 200mm thick medium weight concrete blocks with 50mm cement plaster. The total U value was about 0.5 W/m²K. The internal walls and ceiling were considered as adiabatic, which means there is no heat transfer. Inside visible reflectance from wall surface was 0.5. The ceiling and the floor U values were 2.0 W/m²K and 0.5 W/m²K respectively. Reflectance values for ceiling and floor were taken as 0.7 and 0.2 respectively. Single 3mm thick clear glazing was used for the window. The properties of the existing glazing were as follows: visible transmittance 0.89, solar transmittance 0.83, shading coefficient 1.0 and U value as 0.5 W/m²K.

### 3.3 Indoor Design Conditions

The indoor design conditions were set as follows. The desired internal illuminance was considered as 500lux. The daylight photo sensors were limited to two and their locations were determined by two input data: height above floor and percentage depth of the zone from external vertical window wall. The work plane height was maintained at 0.9m from the floor. Locations for reference points were selected as 50% and 90% of zone depth. Thus reference points were positioned at 3.04 m and 5.7 m from the window pane. The two positions were selected to represent the mid-zone value and deep back value of the considered room. Also, the sensor points were aligned in the center of the length of the window pane.

The maximum light power requirement was set at 20 W/m², the equipment load installed capacity was, 14 W/m² and the indoor design temperature were set to 24°C (75.2 °F) as recommended by the Malaysian Standard for office buildings. The experimental office room was assumed to be used by a single person, in order to minimize the occupants load in terms of energy calculations.

### 3.4 Outdoor Design Conditions

Hourly weather data from the DOE-2 weather file was used for the location, 3.7° N latitude, and 101.6° East longitudes (Kuala Lumpur). The weather data were obtained for the year 2001. The direct and diffuse solar radiation and sky illuminance were calculated for clear sky conditions. Assumptions were made as this data represents tropical climate conditions.

### 3.5 Simulation Analysis Criteria

Analysis of the study was based on the output data obtained from the simulation for the tested overhang options. The simulations on the respective overhang depths were performed for east, west, north and south orientations respectively. The output results were obtained in two forms: hourly values for the designated year and annual energy consumption by end use. The annual results were obtained for the following performance variables: total direct incident solar radiation, total diffuse incident solar radiation, total transmitted heat gains and mean work plane illuminance. The annual energy consumptions by end-use were analyzed for the following performance variables: electricity consumption for cooling, lighting and total electricity.

In this study the work plane illuminance is the sum of direct skylight, reflected skylight, direct sunlight and reflected sunlight reaching the reference points.
The reflected skylight and sunlight is the amount of light reflected from the interior surfaces of the space. Based on the above four components of natural illuminance, the eQUEST-3 simulation program calculates the daylight factors (interior total skylight illuminance divided by exterior horizontal skylight illuminance) and sun illuminance ratio (interior total sunlight illuminance divided by exterior horizontal sunlight illuminance) for 20 different solar altitudes and azimuth values covering the annual range of sun positions. The calculations were performed for standard CIE clear sky conditions. The illuminance contribution from each component is found by interpolating the stored daylight factor and sun illuminance ratio using current hour exterior illuminance obtained from the measured horizontal solar radiation present on the weather file of the location considered. The continuous-off (the electric lights turn off completely when total illuminance level from natural and electric lighting exceeds the required interior illuminance level) control system was used in the simulation to determine the electrical lighting energy needed to make up the difference between the natural illuminance and required work plane illuminance. Finally, the zone electric lighting requirements were passed to the thermal load and energy calculations.

The suggested energy standard for non-residential buildings [486MJ/m$^2$/yr or 135kWh/m$^2$/yr (MS 1525:2001)] was used as a benchmark in describing the energy consumption of the respective tested overhang models. The analysis of each tested overhang model was evaluated for the correspondence performance variable values with base-case model (without overhang). All the performance variables were correlated with overhang ratio (OHR) of the tested overhang models. This gives the designer more flexibility in determining a shading strategy than a fixed depth of an overhang. Also, for better understanding of the optimum energy consumption due to solar heat gains and natural-light utilization, the incremental energy use (IEU) was correlated with shading overhang ratio. The incremental energy use (IEU) is the difference between the electricity consumption (EC) for the base-case model with the respective tested overhang model.

$$\Delta\text{IEU} = \text{EC}_{\text{with shade}} - \text{EC}_{\text{base-case}}$$  \hspace{1cm} (2)

If $\Delta\text{IEU}$ is a positive value, an increase in energy consumption occurs due to the use of shading strategy. If $\Delta\text{IEU}$ is a negative value, a decrease in energy consumption occurs due to the use of shading strategy.

### 4. Results and Discussion

#### 4.1. Impact of Overhang Depth on Solar Radiation Components

The direct and diffuse incident solar radiation and transmitted solar heat gain through the window glass pane were evaluated for the base case model and tested overhang ratios on respective orientations. This enables us to understand the contribution of each solar radiation component on the overall heat transmittance into the building. The analysis was done based on one year of the cumulative sum of direct, diffuse and transmitted heat gains obtained from the simulation. Fig. 2. shows the influence of solar radiation on a bare window for the base-case model.

The results showed that the influence of diffuse component was higher on all orientations than the direct component of solar radiation incident on a window pane. This indicates that in tropical climates, impact of diffuse solar radiation was higher than the direct component of solar radiation. The west orientation received the highest amount of diffuse solar radiation (560.7kW/m$^2$) while the north received the lowest amount of diffuse solar radiation (477.2kW/m$^2$). In comparison, the amount of diffuse solar radiation on the east, north and south received 7.3%, 14.8% and 10.4% less than the west orientation. This indicates that the influence of diffuse incident solar radiation had little effect on window orientation.

![Fig.2. Total Cumulative Solar Radiation Data on Bare Window](image)

The total amount of direct solar radiation received on east window pane was higher than other orientations (370.3kW/m$^2$). This was about 41.6% of total incident solar radiation (direct + diffuse) on the east window surface. In comparison, the amount of direct solar radiation on west, north and south received 9.9%, 59.1% and 48.3% less than east orientation. The influence of direct solar radiation on north was about 21% less than the south orientation. This indicates that effect of direct solar radiation was high on east and west orientations than on the north and south window pane.

The total incident solar radiation on respective orientations showed that the west (894.3kW/m$^2$) and east (889.7kW/m$^2$) received a higher amount of solar radiation than the north (628.6kW/m$^2$) and south (693.5kW/m$^2$) window panes. In comparison, the east and west oriented window panes transmitted about 76.1% while the north and south transmitted 70.7% and 71.4% of the total incident radiation, respectively.
However, the west and east received a higher amount of transmitted heat than the north and south orientations. Hence, the orientation of the window affects the amount of heat transmitted into the building. According to Fig.3., the analysis indicated that the east and west orientations needed larger horizontal overhang ratios (east 1.2 and west 1.6) in order to reduce direct solar radiation incident on a window pane by more than 80%. For north and south orientations, maximum shading from direct solar radiation can be achieved by overhang ratios of 0.6 and 0.8 respectively. This implies that, in order to reduce the maximum amount of direct solar radiation on a window surface, the horizontal overhang depth largely depends on the orientation of the window surface. Further, west and north oriented windows received a maximum and minimum amount of direct solar radiation on the window pane even when solar shading was applied.

Increase in overhang ratio had less impact on the amount of diffuse solar radiation received on the window pane (Fig.4.). Hence, the results indicated that overhang ratio 1.6 reduced diffuse solar radiation incident on windows with an east and west orientation by more than 45%. Similarly, overhang ratio 1.4 reduced diffuse solar radiation on north and south orientations by more than 40%.

Initially the bare window showed a heat gain reduction of between 23.9% and 29.3% on the east, west, north and south orientations compared to the total incident solar radiation on the window surface (Fig.5.). In other words, more than 70% to 76% of incident solar radiation was transmitted through the glazing of the bare window. Horizontal overhang ratio of 1.4 for the north and south indicated 35.9% and 38.3% total heat gain reduction respectively compared to heat gain through bare window. Similarly, east and west indicated 48.9% and 45.4% total heat gain reduction when overhang ratio was 1.6 compared to the base case model.

4.2 Impact of Overhang Depth on Work Plane Illuminance (WPI)

The absolute work plane illuminance (direct sunlight & sky light) were calculated for the respective horizontal overhangs at the two respective reference points inside the office room. The results were obtained for four days (21 March, 22 June, 24 September and 21 December) and for the main cardinal orientations (East, West, North and South). The evaluation of daylight quantity was based on the target absolute work plane illuminance at 500lux. Mean work plane illuminance values were plotted against overhang ratio to determine a general distribution profile of illuminance level received at respective reference points for the tested overhang depths (Figs.6, 7, 8 and 9).

Figs.6, 7, 8 and 9 illustrate that an increase of overhang depth reduced the mean work plane illuminance at both reference points on all orientations considered. Reference point 01 received more than the target illuminance level (500lux) for all overhang depths tested except on 21 December for the overhang ratio 1.4 on north orientations. In December the sun is located in the southern hemisphere, thus the main source of natural light is from the diffuse sky light, which has a comparatively low illuminance compared with that of other orientations.
The high illuminance levels at reference point 01 were mainly due to the amount of direct sunlight received. The mean work plane illuminance below the target level at reference point 02 were received for overhang ratios 1.0, 1.4, 0.4 and 1.0 on east, west, north and south orientations respectively. This indicates that from the point of view of natural-light, deep overhangs can be used on the west orientation, while on north windows, the shading depths have to be limited to very small overhang projections.

4.3 Impact of Overhang Depth on Building Energy Consumption

4.3.1 Base-Case Energy Consumption

Fig.10 shows the annual electricity consumption for base-case generic office rooms obtained on east, west, north and south orientations under tropical climate conditions. Four components, namely, space cooling, area lighting, miscellaneous equipment and ventilation fans contribute to the total office room electricity consumption. In this study, miscellaneous equipment and ventilation fans were set to a constant value for all shading devices tested. However, it can be seen that energy use related to the HVAC system (for space cooling and ventilation fans) dominated the electricity consumption on all four orientations. East and west orientations had the highest effect (55% & 54%) while north and south (50% & 51%) had the least effect on electricity consumption for space cooling of total energy use. As expected, for tropical climates with ample natural-light, electricity consumed for area lighting was relatively insignificant, which accounted for 7.5%, 8%, 8.8% and 8.6% of total energy use on east, west, north and south orientations respectively.

The computed results without natural-light utilization showed significant increase in electricity consumption for area lighting, amounting to 27% and 29% of the total energy use obtained for east, west and north, south orientations respectively. Nevertheless, total climate rejecting design option without shading and without natural-light utilization, yielded 17%, 16%, 8.5% and 10% more than the energy standards, for east, west, north and south orientations respectively.

As illustrated in Fig.11, total energy consumption with a natural-light scheme yielded below the Malaysian energy standard (486 MJ/m²/yr or 135 kWh/m²/yr) for non-residential buildings. The results indicated a 14% reduction on the east and west, 22% reduction on the north and 21% reduction on south oriented office rooms. Nevertheless, total climate rejecting design option without shading and without natural-light utilization, yielded 17%, 16%, 8.5% and 10% more than the energy standards, for east, west, north and south orientations respectively.
4.3.2 Influence of Overhang Depth on Energy Consumption

Influence of overhang depth on energy consumption was determined by analyzing the IEU. The IEU was calculated and compared to the electricity consumed by base-case generic office rooms without external shading devices for space cooling, area lighting and total energy consumption. Energy saving for cooling, lighting and total electricity use was calculated as a percentage compared to base case generic office room energy consumption (Figs.12 and 13).

As shown in Fig.12, with increase of overhang ratio, energy saving for cooling progressively increased and optimum energy saving of 31%, 26%, 19% and 22% were indicated at overhang ratios of between 1.4, 1.3, and 1.2 on east, west and north-south orientations respectively. However, cooling energy saving began to decrease when further increases of the overhang ratio were employed.

Simultaneously, when cooling energy saving reached the optimum range, the lighting energy use increased significantly at above respective overhang ratios by 42%, 39%, 43% and 41%, compared to lighting energy use for base case generic office rooms. As discussed in section 4.2, at overhang ratios 1.4 (405lux, east), 1.3 (390lux, west), 1.2 (330lux, north) and 1.2 (360lux, south), the mean work plane illuminance indicated below 500lux for respective orientations. This suggests the need for electric lighting. Hence, an optimum cooling and lighting energy balance has to be determined by analyzing the total energy consumption.

As illustrated in Fig.13, when overhang ratio increases, the total energy saving curve progressively degrades to overhang ratio 1.0 (east and west), 0.6 (north) and 0.8 (south) and shows a very small additional energy saving beyond these points. Hence, optimum energy savings were indicated at overhang ratios 1.3 on the east, 1.2 on the west, 1.0 on the north and 1.0 on the south orientations respectively. Total energy savings of 14%, 11%, 6% and 8% were obtained compared to base case generic office room energy consumption on the east, west, north and south orientations respectively. Therefore, energy saving values of 14%, 11%, 6% and 8% were determined as optimum savings.

The results mean that work plane illuminances for optimum overhang ratio for total energy consumption were as follows: east (425lux), west (530lux), north (345lux) and south (525lux). This indicated that the west and south received above the target illuminance level while the east and north obtained below the target level. However, the mean illuminance was adequate for general illuminance of office space (above 300lux) on all orientations.

5. Conclusion

This paper has emphasized that the depth of a simple horizontal shading device can be manipulated to control the internal thermal and lighting conditions in order to optimize the energy savings in office buildings in hot and humid climates. A typical Malaysian office room was considered in order to understanding the magnitude of solar heat gain and
natural light penetration when external horizontal solar shading devices were applied. The main findings were summarized as follows:

i) Horizontal overhang ratios 1.2, 1.6, 0.6 and 0.8 reduced more than 80% of the incident solar radiation on window panes in east, west, north and south orientations respectively.

ii) Use of maximum horizontal overhang ratios (1.6 on east, west and 1.4 on north, south) reduced the incident diffuse solar radiation on window panes by almost 50% respectively. However, an increase of horizontal overhang ratio beyond this range had little effect on incident diffused solar radiation.

iii) Transmitted heat gain were reduced 35.9%, 38.3%, 48.9% and 45.4% by horizontal overhang ratios of 1.4 and 1.6 on north, south and east, west orientations compared to the base case model. Also the influence of orientation was more significant on direct incident solar radiation than on diffuse incident solar radiation and transmitted heat gains.

iv) Results on the internal mean illuminance level revealed that a work plane illuminance of 500lux at the back of the room can be achieved by overhang ratios of 1.0, 1.3, 0.4 and 1.0 for east, west, north and south orientations respectively.

v) Optimum total energy savings of 14%, 11%, 6% and 8% were obtained for horizontal overhang ratios of 1.3, 1.2, 1.0 and 1.0 for east, west, north and south orientations respectively.

The study showed that, considering the trade off between total heat gain and natural-light penetration to optimize the total energy consumption as the best option in designing external solar shading in hot and humid climates. These results were promising since solar shading design strategies require a rethinking in terms of energy efficiency and the development of knowledge regarding shading strategies in Malaysia and regions with similar climates.

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