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Adjustable external horizontal shading slats for daylighting in office buildings in Thailand

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Abstract

Heat reflective glass is still preferred by designers of commercial buildings in Thailand to reduce solar gain from windows. This hinders the utilization of abundant natural daylight. Shading slats can block beam radiation and also allow for illumination of interior workspaces by diffuse daylight. This study examines the effective operation and performance of adjustable external horizontal slats installed on south-facing windows in office buildings. Experiments were performed in a full-scale room and the results were used to validate a calculation program for simulation. Three slat adjustment schemes were investigated and compared in terms of indoor daylight characteristics, thermal load, annual energy consumption, and energy savings relative to the common case of unshaded windows with heat reflective glass for typical office working hours. Simulations were performed for rooms of varying dimensions and configurations to establish the energy consumption behaviors for workspaces of different sizes. The study established appropriate monthly slat adjustment angles and determined that the installation of adjustable external horizontal shading slats in office buildings could save up to 60% of total lighting and air-conditioning energy consumption compared to workspaces with unshaded heat reflective glass windows.

Keywords: Daylighting, External slats, Horizontal shading device, Energy saving, Tropical climate

1. Introduction

Commercial buildings in tropical regions are characterized by large, unshaded, glazed windows. Heat reflective glass is commonly used to curb the resultant excessive heat gain, which tends to impede the utilization of abundant natural daylight and necessitates supplementary artificial lighting as a result [1]. Shading slats installed on windows with clear, high visible transmittance glass are a viable alternative for heat-reflective glass because they allow for the penetration of desirable natural daylight into workspaces while preventing solar thermal gain from the window [2,3].

Adjustable shading devices have been studied extensively in different climate zones. They can adapt to variations in outdoor conditions and are therefore preferred over fixed shading devices [4]. Besides reducing heat gain and glare, they grant occupants the freedom to control their working environment and privacy [5]. Yao et al. [6] studied the thermal and visual performance of various adjustable solar shading devices installed in office buildings in Ningbo, China. The behavior of the devices relative to climatic conditions was modeled. An unshaded window with clear glass and another double pane window with low-e glazing were used as the reference cases. Both the simulation and field studies found reductions in the window's solar transmittance by up to 8% while still achieving sufficient workplane illuminance for more than 50% of working hours, which was twice as much as the case of low-e glass. A 30% reduction in total energy consumption was noted in comparison to windows without any shading. Similar studies on external shading devices in Canada [7], Denmark [8], and Hong Kong [9] also found up to 70% reductions in energy consumption. Chaiwiwatworakul et al. [10] and Chaiyapinunt and Worasinchai [11] developed daylight transmission and heat transfer calculation models for windows with shading slats and analyzed their performance in the tropical climate of Thailand. However, they did not examine effective adjustment schemes and energy consumption behavior of workspaces with different dimensions.

Studies focused on the performance of manually-controlled external horizontal slats adjusted monthly remain scarce. This study aims to establish the effective operation and energy-saving performance of this slat configuration over a full year for office spaces of varying sizes. The study focused primarily on south-facing windows. Experiments were conducted in a full-scale room to assess interior daylight distribution and thermal gain through the window. Simulations were performed using a validated program called BESIM to determine the slat adjustment schedules and reductions in lighting and cooling energy consumption from the use of this device relative to the common case of unshaded windows with heat reflective glass.

2. Materials and methods

2.1 Experiments

Physical experiments were carried out to measure daylight from the window with external horizontal slats. In the experiments, the slats were set at different tilt angles on different d; the transmitted and workplane daylight illuminance were measured under varying sky conditions. Figure 1 shows the pictorial view of the laboratory room and the experiment set-up inside the room. As shown, the workplane illuminance was measured along the room center at 10%, 30%, 50%, 70%, and 90% room depth. The thermal performance of the window was investigated by measuring the transmitted solar irradiance and the surface temperatures of the glazing pane and slats. Room air temperature was maintained at 25 °C. Detailed information concerning the experimental facilities is given below. An outdoor laboratory located on the roof of the School of Bio-resources and Technology building at the Bang Khun Tien campus of the King Mongkut's University of Technology Thonburi (latitude 13.7°N and longitude 100.44°E) was used as the experimental site. The room was 9m long and 3m wide with a height of 2.65m measured from the floor to the ceiling.

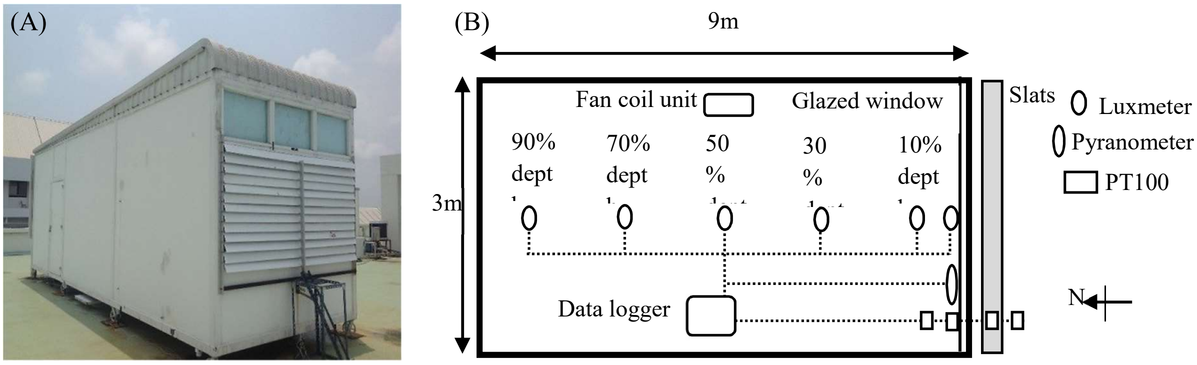

Figure 1 (A) Exterior view of the experiment room, (B) Experimental setup.

The room length-side was laid along a north-south orientation. It had a south-facing window of 2.7m width and 1.3m height. The window sill was 0.7m above the floor. The room ceiling and interior walls were painted white with a reflectance measured at 0.7. The floor reflectance was measured at 0.3. A fan coil unit was installed in the room for space air-conditioning. A set of horizontal slats was mounted outside the glass window to shade the incident beam irradiance. The slats were fabricated from an aluminum sheet painted a white color. The slats had a width of 0.13m and inter-slat separation of 0.10m. According to the room configuration, the area of the window to the total windowed-wall area (or Window-to-wall ratio: WWR) was 0.56. Table 1 summarizes the physical properties of the experimental room, slats, and other surface materials used in the study. All room surfaces and slat surfaces were assumed to be diffusive.

A data acquisition system was used to record all measured data from all sensors at every minute. In this experiment, light sensors were used to measure indoor daylight. Platinum RTD (Pt100) sensors were installed to measure temperatures of the outdoor air, the room air, and the surface of the glazing pane and a slat. A pyranometer was used to measure the transmitted shortwave solar radiation through the window. The experiments were carried out for fully opened slats at 0° and slats tilted downwards at 30° (viewing the ground from the room interior). All measurements were carried out from 8:00 to 17:00, representing typical office working hour.

Table 1 Physical properties of the materials.

Material	Slat Aluminum	Clear glass Glass	Heat reflective glass Glass	Opaque wall Lightweight concrete
Thickness (m)	0.002	0.006	0.012	0.1
Specific heat capacity kJ/kgK)	920	880	840	840
Density (kg/m^3)	2710	2512	2500	620
Conductivity (W/m.K)	205	1.05	1.05	0.16
Visible transmittance	0.0	0.88	0.09	0.0
Visible reflectance	0.8	0.08	0.32	0.5
Solar transmittance	0.0	0.8	0.06	0.0
Solar reflectance	0.8	0.07	0.33	0.5

During experimentation, a meteorological station located at the same campus near the experimental room recorded the global, diffuse horizontal, and beam normal daylight illuminance and solar irradiance, together with the vertical daylight and irradiance on the four cardinal orientations: north, east, south, and west. The temperature and relative humidity of the ambient air were also measured. The data were recorded at one-minute intervals and the recording time was synchronized with that of the experimental data acquisition system. No tall structure presented any obstruction to the station. Data from the experiments were used to validate the simulation program.

2.2 Calculation

A calculation program called BESIM was used to simulate the daylight in an office-like room with a window equipped with external horizontal slats. The program used recorded data from the station as the input and was also validated by [12,13]. The program performs daylight and thermal calculations based on the method outlined by Hien and Chirarattananon [14]. It uses raytracing, flux transfer, and configuration factors for illuminance calculations and incorporates the ASRC-CIE sky model by Perez et al. [15]. BESIM performs heat transfer calculations using energy balance principles and the finite difference method.

A model room was selected to illustrate the energy calculation process. It was rectangular-shaped with a window on the southern wall, as shown in Figure 2. Visible reflectance of the interior wall surfaces was assumed to be equal to 0.5, while that of the ceiling and the floor was 0.8 and 0.3, respectively. The window was made of laminated clear glass with high visible transmittance spanning the entire width of the wall. The room had a depth of 9m, width of 3m, and height of 2.65m from the floor to the ceiling, as well as a window to wall ratio of 0.6. The window sill was 0.85 m above the floor.

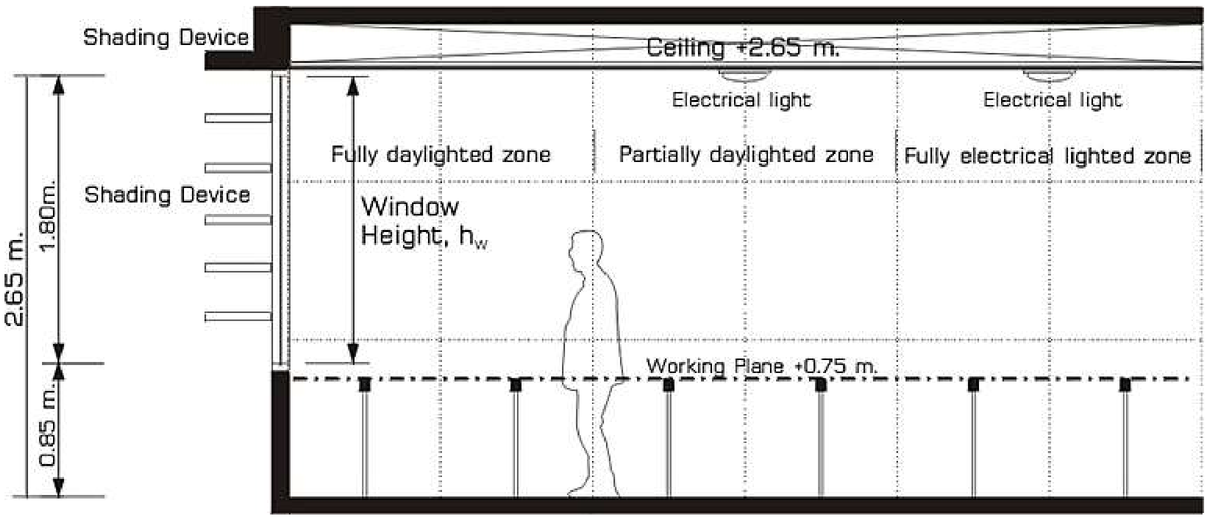

Figure 2 Model office room.

In each simulation case, the hourly results of the transmitted daylight and the workplane daylight were determined throughout the year. Calculation was performed for daylight at 10%, 30%, 50%, 70%, and 90% room depth measured from the windowed wall. The resultant energy for lighting and air-conditioning of the rooms was then calculated when daylighting could supplement the electric lighting and the slats could prevent beam irradiance on the window. The energy-saving potential from daylighting was evaluated against the case of an unshaded window with heat reflective glass.

2.3 Electric lighting

LED lamps with luminous efficacy varying largely from 80-130 lm/W are commonly used in commercial buildings. In this simulation, LED lamps were assumed to be installed on the ceiling of the model room to provide uniform illumination on the workplane. Lamp efficacy was approximately 100 lm/W. Based on the IESNA lumen method illustrated by Equation 1, the calculation indicated that the lighting power density (LPD) was 10.58 W/m^2 for the required workplane illuminance 500 lux, as shown in Table 2.

$$E_w = (LLF)(CU)(L_f / P)(P / A), \tag{1}$$

where E_w is target workplace illuminance, LLF is light loss factor (assumed to be 0.8), CU is coefficient of utilization, L_f / P is the lamp efficacy, and P / A is lighting power density.

Table 2 Specific information for the light luminaire.

Unit	Amount of light
Number of lamps	2
Total light flux (lm)	5360
Total power (W)	58.9
Efficacy (lm/W)	90.9
Work plane luminance (lux)	500
Lighting power density (W/m^2)	10.58

Typically, dimmable lamps are uncommon in office buildings. However, this daylighting study assumed that a dimming controller was integrated with the lighting system to regulate the light from lamps to supplement the daylight from the slatted window. With this control, the LPD of the lighting system varied linearly with the light flux from lamps.

2.4 Air-conditioning

The room was conditioned to maintain the air temperature at 25 °C. The cooling load was calculated from the associated heat from the windowed wall that was the transmitted solar radiation, and the convective heat from the window and the opaque wall section. Electric LED lamps also contributed additional heat to the cooling load when turned on. In the calculation, the dissipated heat from the lamps was postulated to be equal to their electrical energy supply. Equation 2 exhibits the calculation of the cooling energy of the modeled room (*En*) in unit kWh/year.

$$En = \left(LPD + \frac{LPD + HG \cdot (A_W / A_f)}{COP} \right) \cdot A_f \cdot H , \tag{2}$$

where *LPD* stands for the average lighting power density (W/m$_{fl}^2$), *HG* stands for the total heat gain from the windowed-wall (W/m$_w^2$), A_w and A_f are the areas of the windowed wall and the floor area (m^2), respectively. The coefficient of performance (COP) is the coefficient of performance for the air-conditioner assumed to be equal to 2.8. *H* is the total office hours in a year equal to 23:40 h.

2.5 Daylighting schemes

Different daylighting schemes were introduced in the simulations to compare their energy performance. For all schemes, the slat position (angle) was set to shade the sun throughout the office hours (8:00-17:00). For Scheme I, the slats were adjusted monthly with a minimum tilt angle to provide shade from the sun, thus offering a maximum exterior view to building occupants. In Thailand, the sun travels in both southern and northern hemispheres, so the slats could be set at a horizontal position (0°) in months when the sun stayed behind the window. This scheme neglected interior workspace properties and daylight requirements. In Scheme II, the slats were assumed to be fixed at an angle for sun shading over the course of the year. This simple scheme was considered to represent a typical shading design where slats were not adjustable. The scheme was used to compare energy performance between adjustable slats and fixed slats. The shading angles of the above two schemes were determined using the slat configuration and window orientation relative to the sun's path.

For Scheme III that minimized the lighting and air-conditioning energy, however, detailed simulations were carried out to identify the slat adjustment angle for each month. This scheme took into account the effects of several factors including window size, glazing properties, room configuration, and desired workplace illuminance to establish the angles that provided shade but introduced more daylight to save energy. Table 1 provides the visible and solar properties of the heat reflective glass used in this study.

2.6 Different room geometry

In the second part of the simulation study, the procedure described for the model room was replicated in 45 different workspaces with varying room depth (D), width (W), and window-to-wall ratio (WWR). The rooms were assumed to be of similar properties to the model room. To investigate the dependency of the interior daylight on the room configurations, the side-length of the windowed-wall was varied from 3.0 m up to 15.0 m. The depth from the windowed-wall to the opposite rear wall was also varied from 3.0 m up to 15 m.

3. Results and discussion

3.1 Experiments

On the 20th of December 2018, an experiment was performed for a south-facing window with slats at 0°. The measured results are given in Figure 3 below. It was observed that the sky was quite clear on the day of the experiment. The global illuminance (E_{vg}) reached 70 klux, while the solar irradiance (E_{eg}) was 700 W/m^2 at noon (Figure 3 (A) and (B)). The sky diffuse components (E_{vd} and E_{ed}) were high during morning hours, but dropped in the afternoon as the beam component increased. Even though the sun appeared in front of the window for the entire day, the transmitted daylight was only 2-5klux or approximately 10% of the total vertical illuminance values.

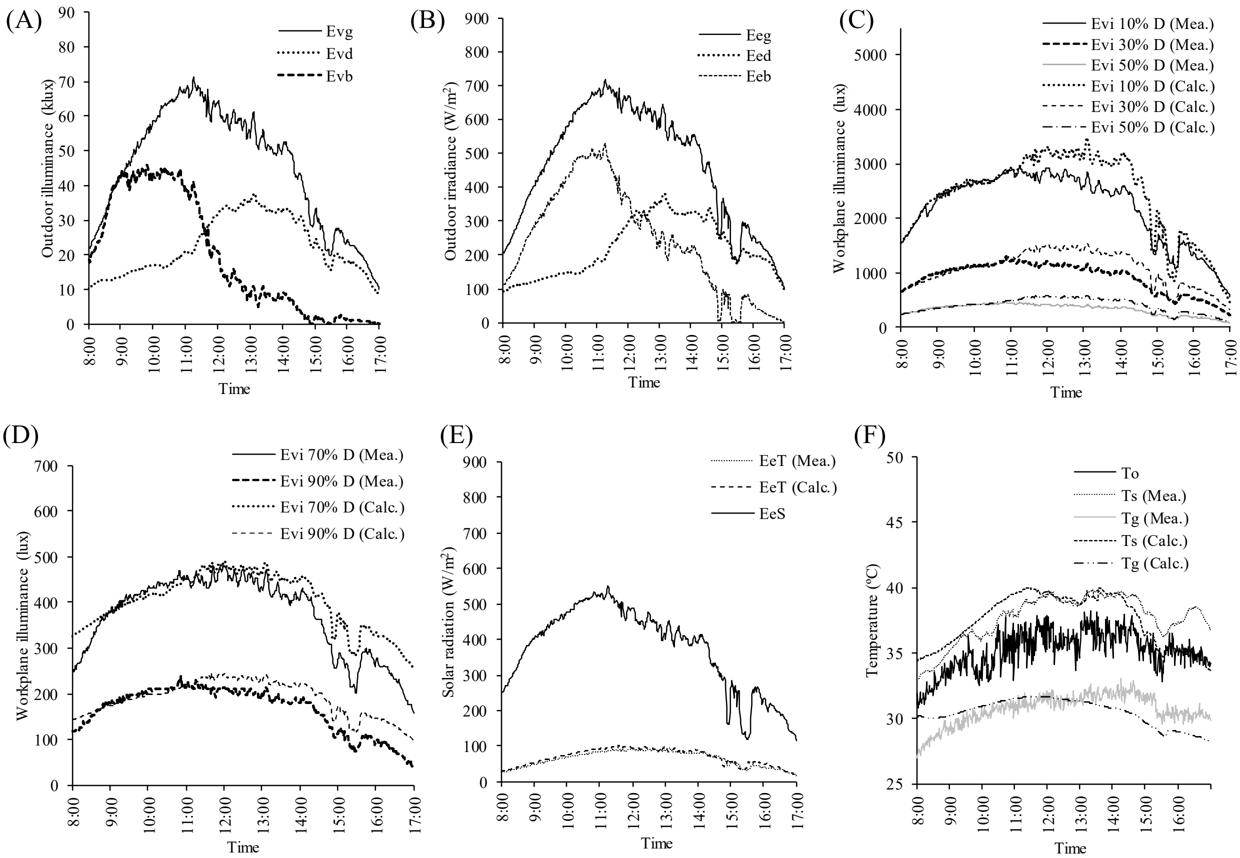

Figure 3 Experiment on daylight from a south-facing window with slats at 0°, (A) Outdoor daylight,(B) Outdoor irradiance, (C) Workplane illuminance (10%D to 50%D), (D) Workplane illuminance (70%D & 90%D), (E) Transmitted radiation, (F) Temperature.

In the experimental room, the workplane illuminance (E_{vi}) near the window (10%D and 30%D) was higher than 500 lux for most of the measured period. This illumination level was sufficient for office tasks. Near the rear wall (70%D and 90%D), the illuminance dropped to 100-300 lux, which was still applicable for general lighting (Figure. 3(C) and (D)). The transmitted radiation (E_{eT}) was 5 times less than incident radiation on the vertical plane (E_{eS}), as shown in Figure 3 (E). The measured and calculated temperatures of the slats (T_s), glass

(T_g), and outdoor air (T_o) are shown in Figure 3 (F). Glass temperature was slightly lower than outdoor air temperature (3 °C less at noon), whereas slat temperature was higher than the latter (2 °C higher at noon). The trend was similar for all examined surfaces.

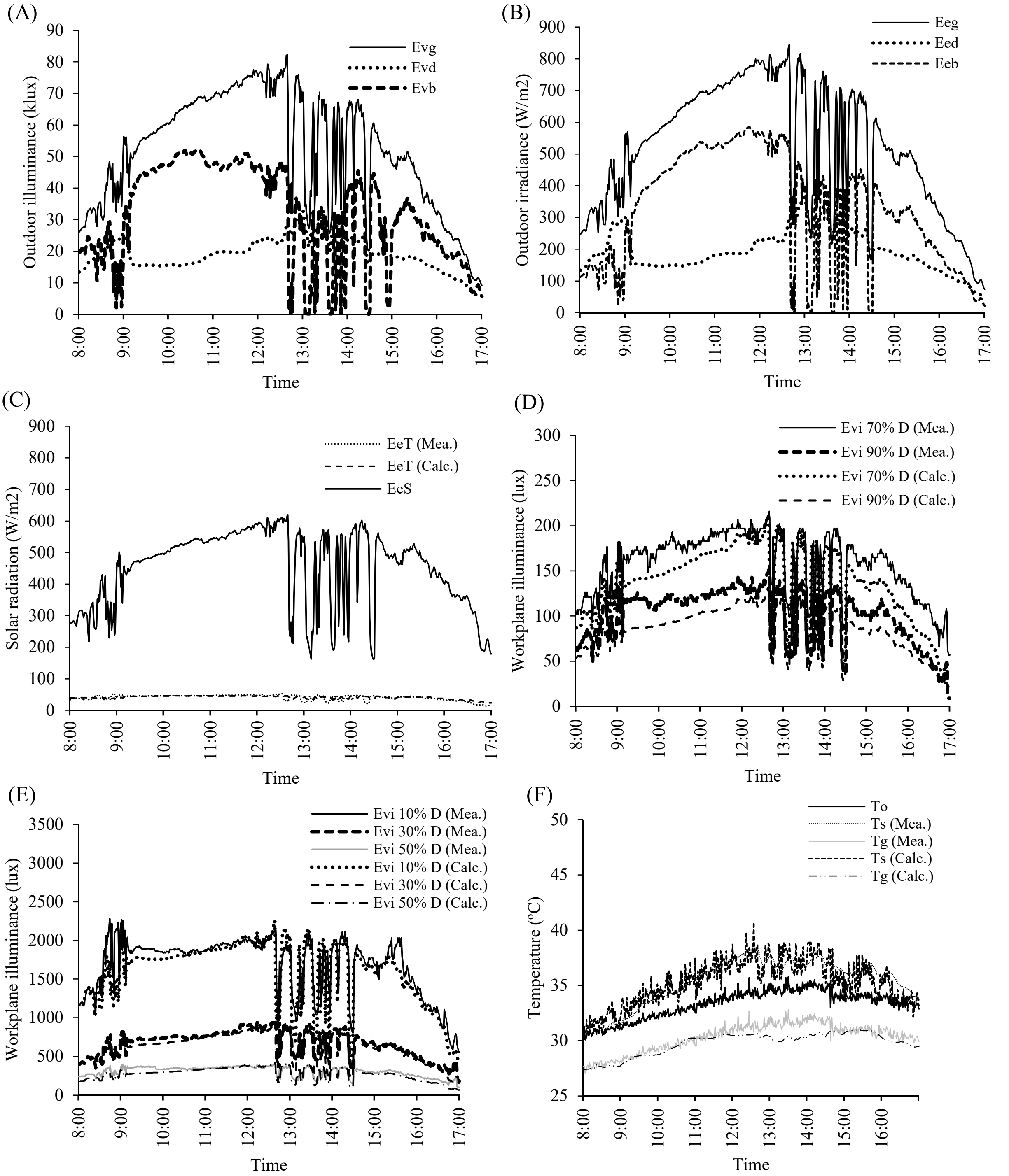

Figure 4 Experiment on daylight from a south-facing window with slats at 30°,(A) Outdoor daylight,(B) Outdoor irradiance, (C) Workplane illuminance (10%D to 50%D), (D) Workplane illuminance (70%D & 90%D), (E) Transmitted radiation, (F) Temperature.

On the 24th of December 2018, another experiment was carried out for slats angled at 30°. On this day, the sky was partly cloudy with largely variable outdoor daylight. However, the daylight was still excessive and global illuminance reached 60-70 klux (Figure 4(A)). The corresponding solar irradiances are given in Figure 4 (B). Tilting the slats to 30° intercepted more daylight and radiation compared to the slats at 0°. However, the workplane illuminance near the window was sufficient for office tasks without additional electric lighting (Fig.

4(C)). In this experiment, reducing the transmitted daylight improved the illumination quality as excessive daylight was alleviated. The variation of workplane illuminance was also alleviated by the slats, despite the considerable and rapid fluctuation of the outdoor daylight.

The measured and calculated results for both experiments were consistent, as shown by the root mean square difference (RMSD) and mean bias difference (MBD) values in Table 3 calculated using Equations 3 and 4.

$$MBD = \frac{1}{N}\sum_{i=1}^{N}(C_i - M_i)\,, \tag{3}$$

$$RMSD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(C_i - M_i)^2}\,, \tag{4}$$

where C_i is the calculated value, M_i is the corresponding measured experimental value, and N is the number of data points considered.

Table 3 RMSD and MBD of experimental measurements and calculations from BESIM program.

Slat angle	Evaluator	E_{vT} (lux)	E_{eT} (W/m^2)	$E_{vi\,(10\%\,D)}$ (lux)	$E_{vi\,(50\%\,D)}$ (lux)	$E_{vi\,(90\%\,D)}$ (lux)	T_s (°C)	T_g (°C)
0°	RMSD	1,347.08	7.09	327.02	94.57	32.81	1.47	1.09
	MBD	589.63	4.65	216.07	69.72	24.15	-0.22	-0.39
30°	RMSD	1,031.91	5.98	232.62	52.08	23.28	1.05	0.80
	MBD	-83.62	0.05	-89.38	-29.44	-18.19	-0.44	-0.55

3.2 Simulation results

The validated program was used to simulate indoor daylight from the three adjustment schemes with external horizontal slats. The associated solar and heat gains from daylighting were calculated. The full-year hourly records of the outdoor daylight and solar irradiance from the meteorological station were used for the simulations.

3.3 Model room

Based on slat configuration (slat width and separation) relative to the path of the sun in the study location, Figure 5 (A) exhibits the slat angles that maximized the exterior view without beam penetration (denoted as MV). The slats were set at 0° from May to September. The maximum tilt angle was 30° from December to January, when the sun appeared in front of the window with low elevation. For the scheme of the fixed slats (FS), the angle was set at 30° all year round. To determine the optimum angle for the minimum energy scheme (ME), simulations were carried out for all possible angles in the shaded area in Figure 5 (A). The determination accounted for influences of the window and room shape as well as the required workplane illuminance. The centerline superimposed in the figure also presents the minimum energy consumption scheme derived for the model room.

3.4 Transmitted daylight

Figure 5 (B) shows the monthly average for the hourly values of daylight illuminance on the south façade segregated into the total, diffuse, and beam components. The plot indicates that the total daylight during the office hours (8:00-17:00) was about 11-15 klux between May and August when the sun travelled towards the north. However, the value increased in the remaining months up to 48 klux in December. The larger value was due to the incidence of the beam component on the facade.

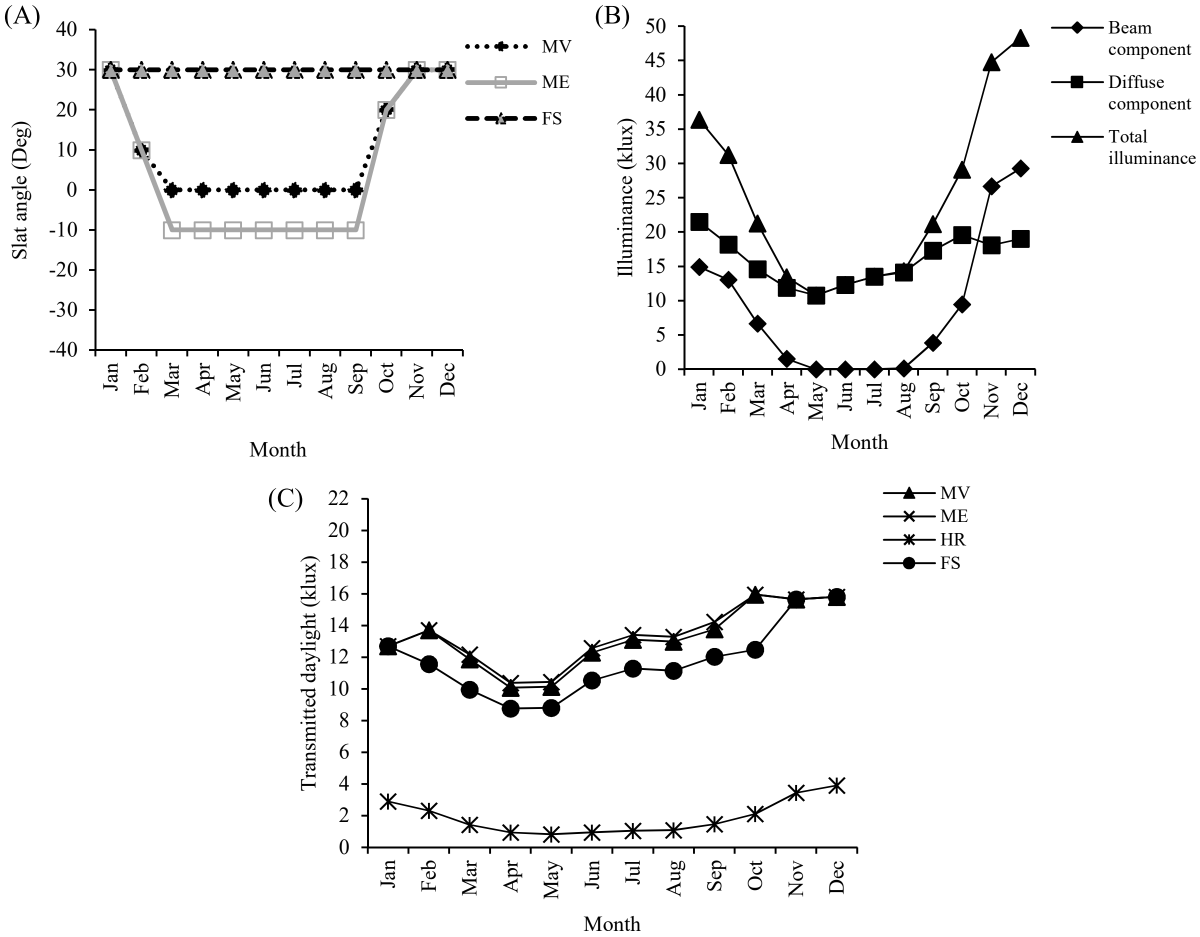

Figure 5 Slat adjustment schemes and daylight illuminance on the south façade, (A) Slat adjustment schemes, (B) Daylight on the south window, (C) Transmitted daylight.

Figure 5 (C) shows the daylight transmission of the three schemes. For the maximum view scheme, the transmitted daylight was within a range of 10-16 klux. The slats could effectively moderate the large exterior daylight variation. Although the window was shaded, there was slightly less transmitted daylight than the diffuse daylight since part of the incident beam was reflected by the slats onto the glazing pane. Examining the fixed angle scheme, transmitted daylight was 2-3 klux less than that of the maximum view scheme, except between November and January, as the slats were at the same tilted angle. However, the shaded window transmitted 4 times more daylight when benchmarked with the conventional window design using the heat-reflective glass (HR). The minimum energy consumption scheme introduced slightly more daylight than the maximum view scheme between March and September, resulting in reduced total energy consumption.

3.5 Workplane illuminance

Daylighting effectiveness from the external slats was investigated considering interior illumination. Figure 6 characterizes the workplane illuminance by its average mean values, average maximum values, and average minimum values. The room depth/window height ratios (D/H) of the model room were plotted on the x-axis to represent the five workplane points examined in the study. Under the minimum energy scheme, average workplane illuminance was as high as 2,000-3,500 lux near the windowed-wall (D/H=0.5). The maximum average value could reach 5,000 lux when the slat aperture was turned towards the sky in September and the average minimum value was around 800 lux with extensive sun shading in December. The average daylight trend line is skewed towards the maximum average, indicating less frequency of occurrence for minimum daylight. The month of June was selected to represent the period when the sun travels northwards and slat tilt angles are different for each scheme. However, the three schemes share the same slat angle of 30° during the sun-facing period, meaning similar daylight characteristics. Workplane illuminance under the maximum view scheme was 100-300 lux lower than the minimum energy scheme (at D/H=0.5), but comparable.

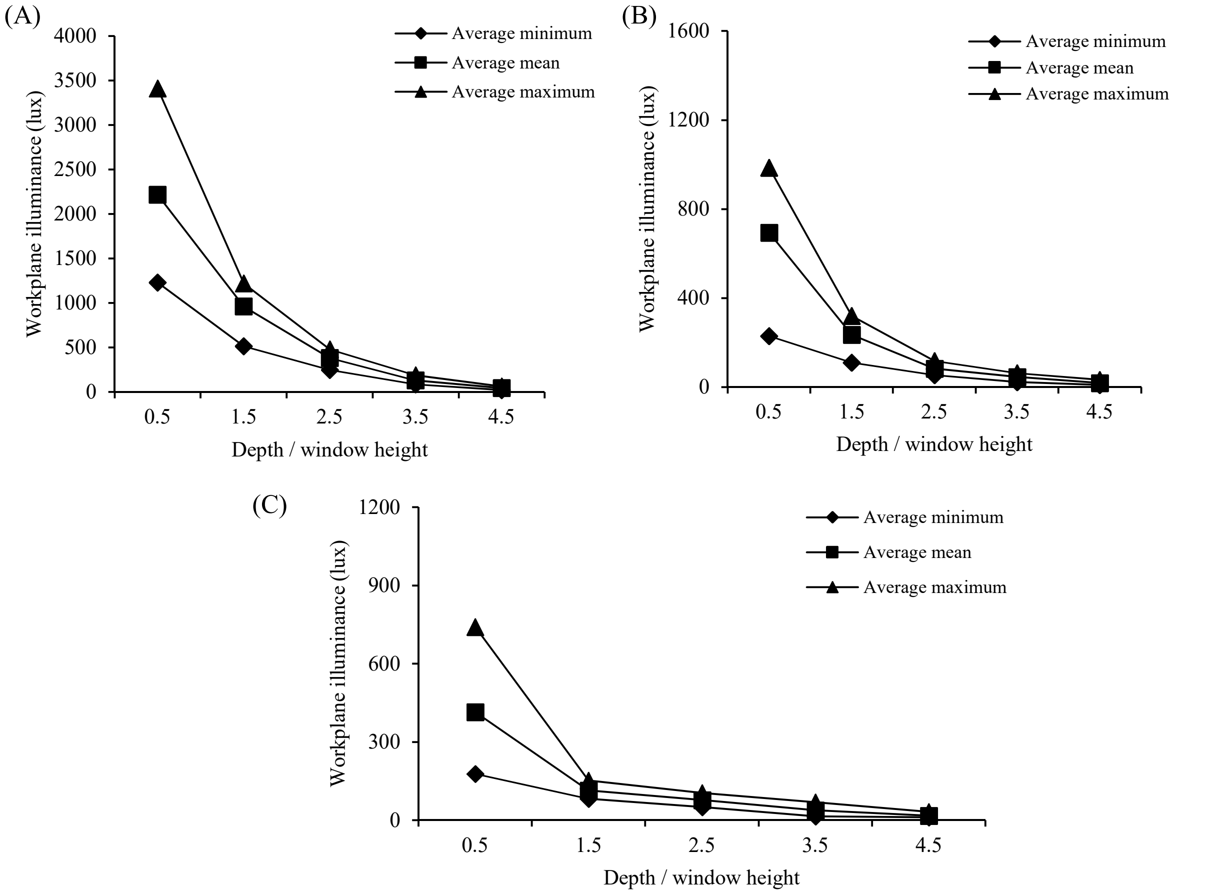

Figure 6 Workplane illuminance in June, (A) Minimum energy scheme, (B) Fixed angle scheme, (C) Heat reflective glass.

The day-lit room could be arranged into three zones along the room depth: fully-daylighted zone, partially-daylighted zone, and fully-electric lighted zone. Based on the workplane illuminance requirement of 500 lux, the fully-daylighted zone where the daylight was sufficient for interior illumination extended from the windowed-wall depth up to D/H=1.5. However, application in this zone would require additional local shading for the working stations to reduce the amount of daylight. Intuitively, the daylight dropped exponentially along the room depth. In the extended space from D/H=1.5 up to D/H=3.5, the zone had lower daylight variation within a range of 100-2,000 lux. To meet the target illuminance of 500 lux, this zone required supplementary electric lighting and was considered a partially-daylighted zone. Deeper than D/H=3.5, the average maximum daylight value was less than 500 lux and electric lighting was required for the majority of office hours. For this zone, full-time electric lighting was required and could thus be defined as a fully-electric lighted zone.

Adjusting the slats appropriately maintained the transmission and distribution of daylight on the workplane at suitable levels throughout the year. Figure 6 (B) presents the workplane illuminance for fixed slats at 30°. In comparison with the previous schemes, the workplane illuminance was 2 klux lower and offered a smaller zone of useful daylight. For the window with heat reflective glass, the daylight zone was the smallest. It was also noted that beam illuminance could penetrate the room with heat reflective glass during the sun-facing period.

3.6 Solar thermal gains

The solar and thermal gains from daylighting using the window with slats influence the amount of electrical energy required for cooling. In this analysis, the cooling load comprised the thermal load from the window and opaque wall section and also the dissipated heat from electric lighting.

Figures 7 (A) and (B) show the vertical solar irradiance on the south plane and solar transmission according to the three slat control schemes. The variations corresponded with their associated daylight illuminance (Figure 5). Figures 7 (C), (D), (E), and (F) show the total thermal load from the different schemes calculated monthly, excluding weekends. The thermal load for the maximum view scheme was observed to be comparable with that of the minimum energy scheme. For the window section, the major share of the thermal load was due to the transmitted irradiance. This emphasized the importance of using sun shading in tropical regions. It was noted that the clear glazed window equipped with sun shading produced less thermal load than the heat reflective glass without shading. Daylight used to supplement electric lighting reduced the thermal load from lighting. Consequently, the total thermal load for cooling due to lighting was 50% less than in the case of heat reflective glass.

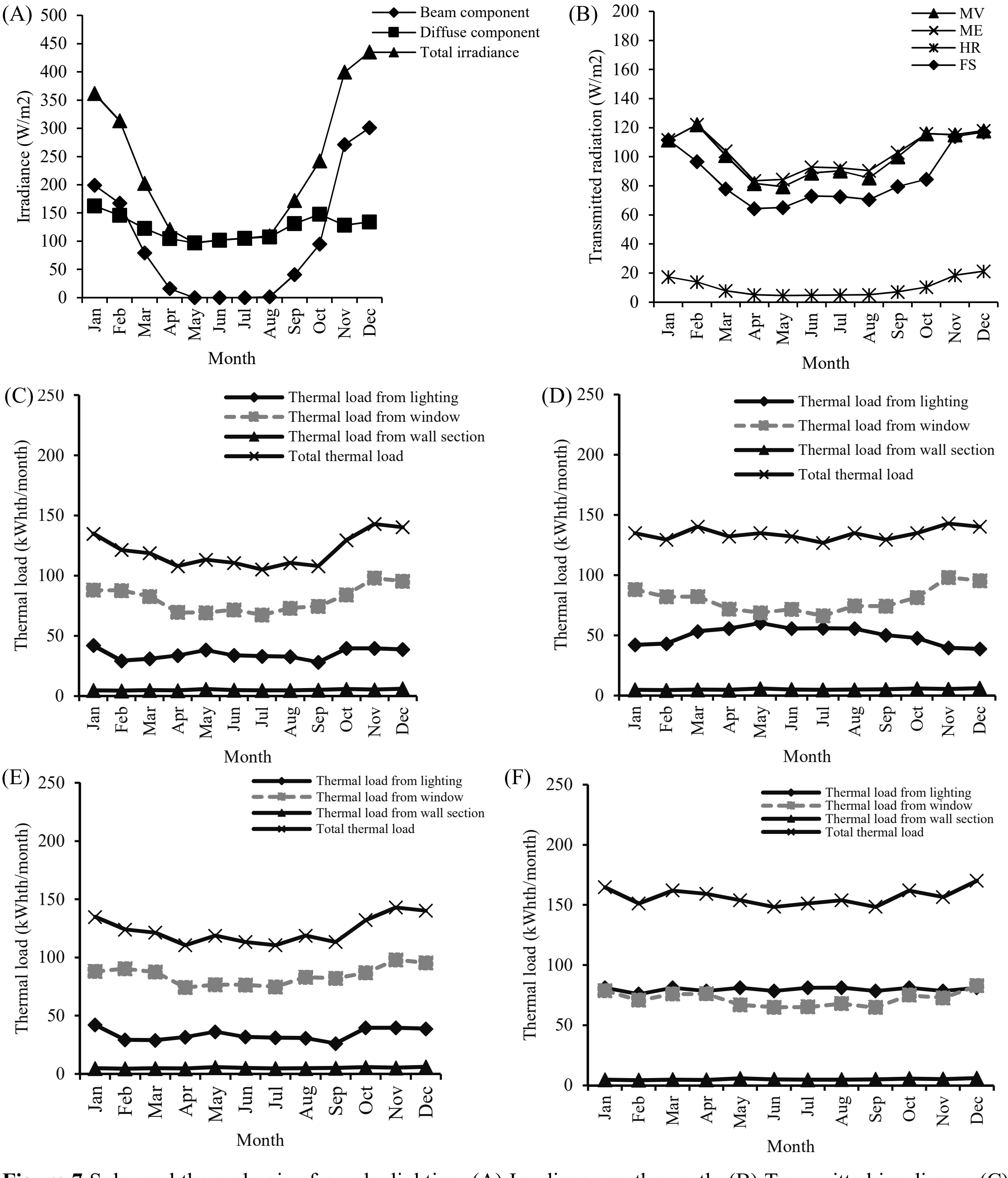

Figure 7 Solar and thermal gains from daylighting, (A) Irradiance on the south, (B) Transmitted irradiance, (C) Minimum energy scheme, (D) Maximum view scheme, (E) Fixed angle scheme, (F) Heat reflective glass.

3.7 Energy consumption

The study assumed that the lamps were dimmable and provided a uniform illuminance of 500 lux on the workplane level (0.75 m). Specific information concerning the luminaires is shown in Table 2. The lighting system regulated the lamps for supplementary artificial lighting. Figure 8 shows the average lighting power density (LPD) for a workplane illuminance of 500 lux. The average LPD was plotted against D/H for June. It was observed that the LPD for slats operated under the minimum energy consumption scheme was lower than the others. This could be attributed to the higher daylight distribution to meet the required illuminance. The lighting energy consumption for the three control schemes is shown in Figure 8(B). Among them, the highest consumption is for fixed-angle slats. The two adjustable slat schemes consumed about 20% less energy than the fixed slats.

The cooling energy was derived from the total solar and heat gains from the window and the opaque sections of the whole windowed wall. The COP=2.8 was assumed for the air-conditioning unit, and the monthly cooling energy consumption is shown in Figure 8(C). The cooling energy consumption for adjustable external slats was slightly higher than that for the unshaded heat reflective glass. External slats with clear high-transmittance glass enable more daylight penetration and less convective heat transfer than heat reflective glass, but admit higher radiation. The reduction is attributed to lower total heat gain from the window and lighting. Figure 8 (D) shows the total monthly energy consumption from the simulations. For the selected model room, it was observed that lighting energy contributed significantly to the total energy requirement. Despite yielding higher cooling energy consumption, the minimum energy scheme consumed 50% less lighting energy, meaning lower overall total energy consumption than in the case of heat reflective glass. In terms of energy-saving performance, this scheme was determined to be the most preferable.

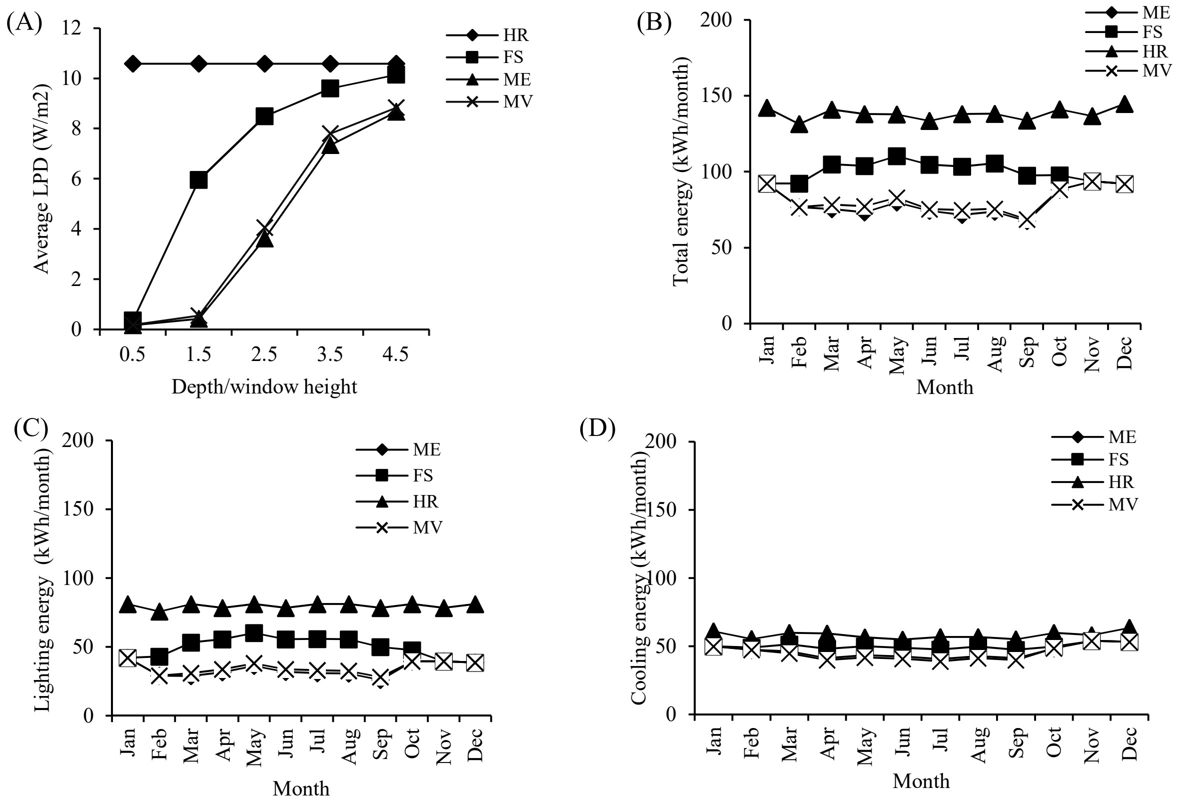

Figure 8 Energy consumption from daylighting, (A) Lighting power density in June, (B) Lighting energy, (C) Cooling energy, (D) Total energy.

3.8 Rooms of different geometry

Similar simulations were carried out using the procedure outlined above to determine the slat control schedule that minimized energy consumption (the ME scheme) for a different window to wall ratio (WWR), room width (W), and room depth (D), representing the dynamic shapes of office spaces. The WWR values were set at 0.3 for a room with a small window, 0.6 for a room with a medium window size, and 0.9 for a room with a large curtain window. The width-side wall of the room on which the window was situated was varied from 3m to 15m. The room depth that was measured from the windowed wall was varied for 3m, representing a shallow room up to 9m representing a deep room. In all cases, the window was oriented southward and the slats possessed an identical configuration to that of the experimental room. The required workplane illuminance was 500 lux.

Examining the simulation results in Figures 9 (A)-(C), the slats were adjusted downward at an angle of 20°-30° from horizontal (fully open position) for the shallow room (D=3.0 m) with the medium and large window (WWR>0.6) to shade more excessive daylight throughout a year. For the shallow room with a small window (WWR 0.3), however, the slats would turn upward at 10° from the horizontal position to introduce more daylight between April-September when the sun stayed overhead and travelled the northern hemisphere of the study site. For deeper rooms (D>6m), Figures 9 (D)-(I) indicated the identical schedule of the slat adjustment that introduced the most daylight.

In Figures 10 (A)-(C), the annual lighting and cooling energy consumption of the rooms with the slat windows were calculated and evaluated against similar rooms with heat reflective glass windows. Consumption was presented in terms of total electrical energy consumed by the rooms per year based on kilowatt-hour units per year. It was observed that room energy consumption increased with increasing floor area (D x W) and window area (WWR). However, the rooms using daylight from a window with slats consumed less energy than the rooms with heat reflective glass.

In Figures 10 (D)-(F), the corresponding energy savings when using daylight from the window with slats are presented. Overall, 10-60% of the electricity consumption in the room could be saved from daylighting. The figures also raised some key points that the window size (WWR) influenced potential savings. For the shallow rooms (D=3m), a larger window was not as energy efficient as a small window, despite being equipped with adjustable slats. For the deeper rooms (D>6m), a large window was more efficient as it introduced more daylight deeper into the workspace. The extension of the windowsill from the workplane level to floor level (increasing the WWR from 0.6 to 0.9) did not improve the benefit from daylighting as the resultant increase in heat gain was more substantial than additional daylight illuminance on the work plane. However, the energy difference was limited to about 5% due to the use of adjustable external shading slats.

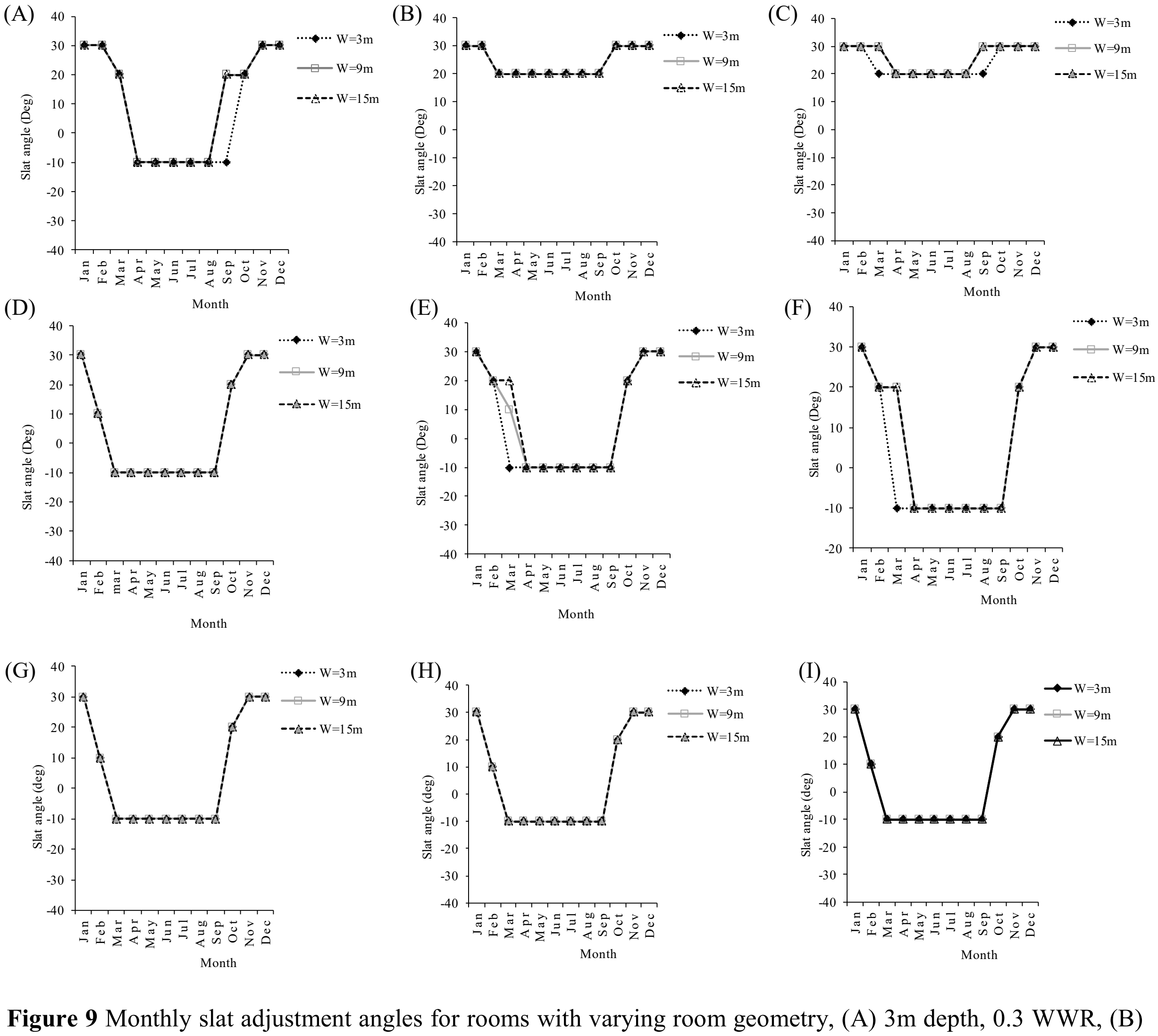

Figure 9 Monthly slat adjustment angles for rooms with varying room geometry, (A) 3m depth, 0.3 WWR, (B) 3m depth, 0.6 WWR, (C) 3m depth, 0.9 WWR, (D) 6m depth, 0.3 WWR, (E) 6m depth, 0.6 WWR, (F) 6m depth, 0.9 WWR, (G) 9m depth, 0.3 WWR, (H) 9m depth, 0.6 WWR,(I) 9m depth, 0.9 WWR.

Additional analysis was carried out to assess the daylighting quality from the window with slats by adopting the useful daylight illuminance paradigm (UDI) proposed by Nabil and Mardaljevic [16]. The period for annual working hours, when workplane illuminance fell between 100 lux (lower limit above which illuminance is considered useful) and 2000 lux (upper limit above which illuminance is considered too high and undesirable), was computed as a percentage of the entire work year. Figure 11 presents the UDI of the rooms with the two slats control schemes: ME-minimum energy and FS-Fixed slat angle.It was acknowledged that the UDI is dependent on the positions considered in the day-lit room. However, the average UDI value of the five points at 10%, 30%, 50%, 70%, and 90% of the room depth were used to present in Figure 11. It was observed that the ME-scheme could offer higher UDI values for rooms deeper than 6m (D>6m). The FS scheme was slightly better in the case of a shallow room (D=3m).

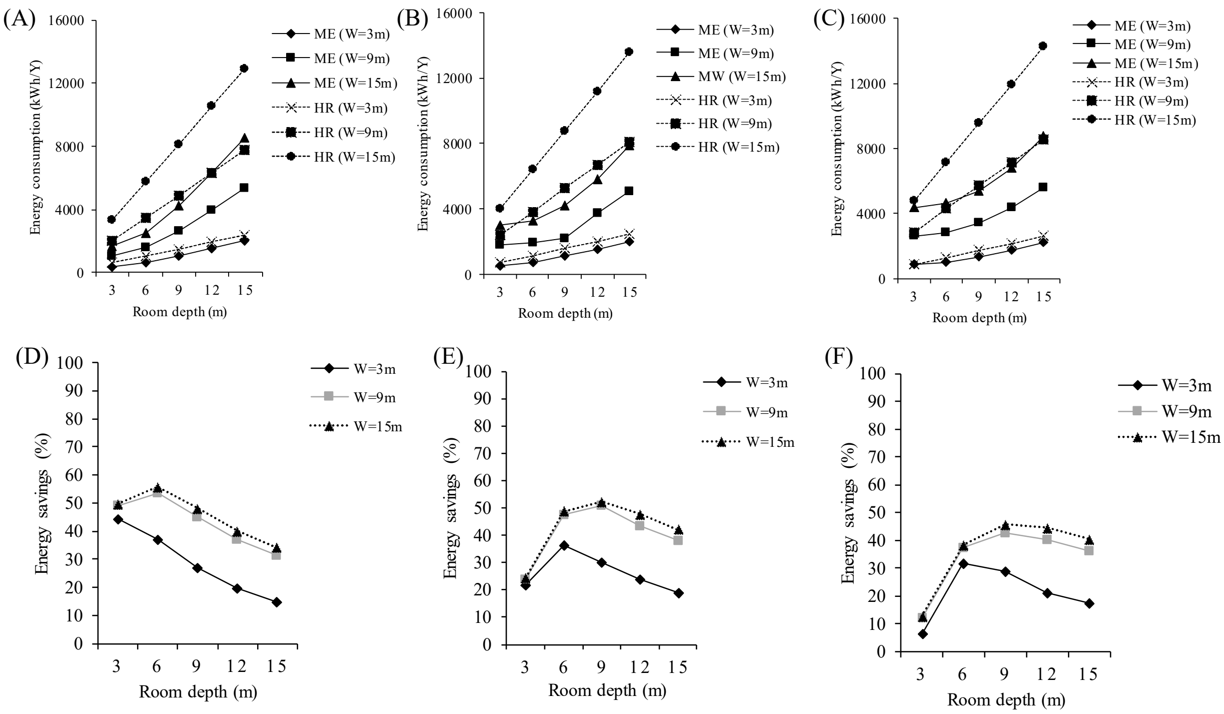

Figure 10 Total energy consumption and energy savings for rooms of different geometry, (A) WWR = 0.3, (B) WWR = 0.6, (C) WWR = 0.9, (D) WWR = 0.3, (E) WWR = 0.6, (F) WWR = 0.9.

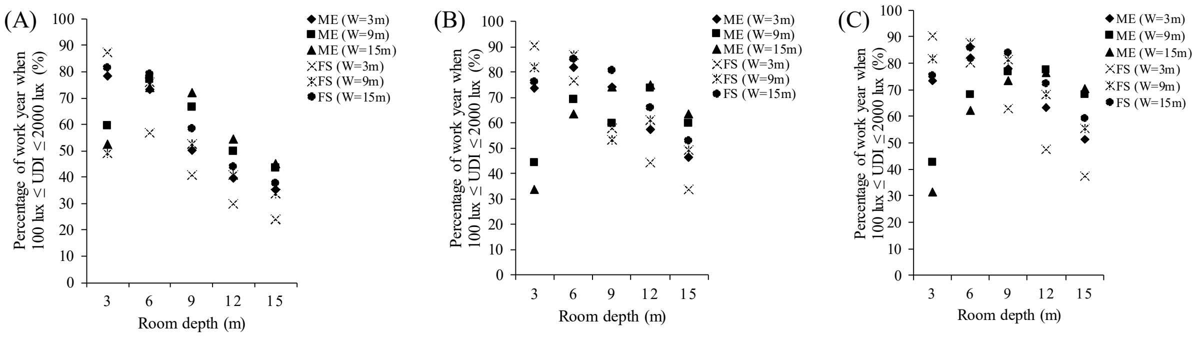

Figure 11 Useful daylight illuminance (UDI) from the south-facing window with external slats, (A) WWR = 0.3, (B) WWR = 0.6, (C) WWR = 0.9.

4. Conclusion

Daylighting using windows with external horizontal slats was investigated for office rooms in a tropical climate. The slats presented an effective means to provide shade from direct sunlight in the tropics where the sun travels overhead for most of the day. A shallow slat angle of 20-30 degrees was sufficient to intercept the sunlight and prevent it from entering a south-facing window. Appropriate adjustment of the slats regulated workplane illuminance to meet indoor lighting requirements. It also moderated the amount of daylight variation and improved the indoor daylight environment. In this study, experiments were performed and gained results that accurately validated the BESIM simulation program.

Daylighting using external horizontal slats was considered for three schemes: (1) Monthly slat adjustment to maximize the outdoor view, (2) monthly slat adjustment to minimize the energy consumption, and (3) slats fixed at an angle to provide shade from sunlight throughout the year. All schemes could block direct sunlight and were assessed in terms of indoor illumination provision, associated cooling load, and total energy consumption for lighting and cooling. The UDI analysis indicated that the schemes using the adjustable slats could control the workplane daylight illuminance within the useful range of 100-2,000 lux for 60% up to 90% of the annual working hours, while the scheme using fixed slats did not perform as effectively.

Simulations by the validated program also calculated the heat associated with daylighting using adjustable external slats. The heat gain included transmitted solar irradiance, heat gain from the shaded window and opaque wall section, and heat from electric lamps. The calculations showed that heat gain from the daylighting was lower than in the case of heat reflective glass windows with non-dimmable lighting. By varying the room and window configurations, the office rooms utilizing daylighting consumed 10-60% less energy than those with heat reflective glass. External shading slats adjusted monthly were determined to be a viable replacement for heat reflective glass in office buildings. However, the slat adjustment scheme to maximize the view and scheme to minimize energy were comparable. The difference in energy savings from the two schemes was less than 5%, though the latter scheme was preferable in terms of energy-saving performance. For occupants who appreciate slat control with less complexity, the maximum view scheme could be adopted.

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