Energy Saving Potential from Daylighting through External Multiple-Slat Shaded Window in the Tropics

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Abstract-Sunlight is strong and skylight is voluminous in the tropics. External multiple horizontal slats are simple but effective to shade the direct sunlight from north- and south-facing windows of a building in a tropical region. The device still allows the skylight to pass through and offers comfortable viewing from the interior to the exterior scene. This paper presents technical results of an experimental and simulation study on the use of such device with windows. The paper demonstrates an optimization of energy benefit from using such device on appropriate size of and suitable type of the glazed window.

Keywords-Daylighting, Glazing performance, Multiple-slat shading.

1. Introduction

Thailand is situated in the tropics where the climate is hot and humid and the daylight is abundant throughout a year. It was reported that the daylight illuminance on window during 8:00-17:00 exceeds 5 klux more than 90% of the time with regardless of orientation [1]. Large glazed windows are popular features in the present trend of building design in Thailand. Solar radiation through the large windows causes excessive heat gain and thermal problems. However, consulting engineers and architects commonly recommend the use of the dark heat reflective (coated) glazing. These practices reduce substantially daylight illumination in building interior and lead to fully electric lighting. Typically, air-conditioning and electric lighting are responsible respectively for 50% and 20% of electricity consumption in such buildings [2].

In the tropics, exterior shading with multiple horizontal slats can effectively shade radiation of the sun beam from window on north or south façade. It still allows skylight to penetrate the window to give a soft natural daylight in the room. Multiple slats, spaced appropriately, will allow sufficient view out through the window, enable application of daylighting and reduces cooling load.

The daylighting through external multiple slats have been studied in various locations mostly from cold climate and subtropical climate. In Jordan, Alzoubi and Al-Zoubi [3] used a simulation program namely "Lightscape" to determine the daylight penetration through multiple slats affixed on window of a typical office model. The electric lighting energy savings was calculated based on a continuous dimming scheme with an illuminance target of 500 lux. It was found that the shading device with the chosen dimensions offered the highest reduction in lighting energy. In Taiwan, Cheng et al. [4] conducted an outdoor experiment using a scale model of a room equipped with external multiple slats. The authors concluded that the device was able to reflect daylight from sun and sky into deeper interior space. Chaiwiwatworakul et al. [5] reported a study on application of automated slats placed between two glass panes at the window of a room equipped with dimmable electric lights. The system operated automatically to minimize electric lighting energy while maintaining good visual quality. The authors found lighting energy savings of

80%. The above studies examined particularly energy associated with lighting system.

A study of Greenup et al. [6] emphasized the essence to use a computer program that can accurately predict quantitatively and qualitatively daylight condition in a space and at the same time able to model interior thermal environment adequately. Under Belgium climate, Bodart and Herde [7] coupled ADELINE and TRNSYS programs to simulate daylight entry and dimming of electric light in a room model as well as corresponding heating demand all year round. Tzempelikos and Athienitis [8] simulated a room daylighted through shaded window and obtained estimation of lighting and cooling energy under a continuous dimming scheme. Annual cooling and lighting energy demand was plotted against transmittance of shading system that exhibited inflexion points. Hviid et al. [9] developed a method for calculation of direct and diffuse daylight transmission through shaded window and used a European software for calculating associated heat transmission. Ferraro et al. [10] presented a radiosity method for calculation of interior illuminance resulting from transmission of both daylight from the sun and that from the sky, given any sky luminance model or given measured data.

Among the studies, there were typically found that an absolute target of the interior daylight illuminance was defined for evaluating performance of a daylighting system. However, Nabil and Mardaljevic [11, 12] recommended a more suitable method. Daylighting design should target for a range of 100-2,000 lux and estimates the conditions of occurrences of daylight illuminance under 100 lux and those over 2,000 lux. The authors called the approach “Useful Daylight Illuminance” and illustrated that the approach leads to higher level of occupant satisfaction and energy saving.

This paper presents an optimization of a window with external multiple slats for daylighting in a tropical climate. The study focused particularly on the south windowed-wall. Full-scale physical experiments were conducted to evaluate the transmitted interior daylight illuminance and its distribution. Simulation using a validated program called “BESIM” was then performed to evaluate the reduction of energy consumptions from both lighting system due to artificial light from lamps supplemented by the daylight and air-conditioning system due to cooling load reduction. The results inferred that there is an optimum size of the window with the device in relation to overall size of the wall.

2. Experimental Setup

A series of experiments was conducted in a room of a laboratory building whose glazed window on south-facing wall was affixed with external multiple slats. The building is located on an outdoor area in Bangkhuntian campus of the King Mongkut’s University of Technology, Thonburi, (Latitude 13.6°N and longitude 100.4°E), in southwest of Bangkok. A daylight and solar radiation measurement station is also located in the same area.

2.1. Daylight and Solar Radiation Measurement Station

A set of daylight and solar radiation sensors has been installed on the roof deck of a seven-storey building of the School of Bioresources and Technology on the campus. The set of sensors includes those that measure global, diffuse horizontal, and beam normal components of daylight and solar radiation. The station is also equipped with sensors to measure vertical illuminance and solar radiation, zenith luminance, air temperature and humidity sensors, and sky luminance distribution. All data from the sensors have been logged and recorded on a personal computer. Fig. 1 shows photographs of the station and the experimental building.

(a) Daylight measurement station

(b) The experimental building

Fig. 1. Photographs of the main facilities for the experiments

2.2. Experimental Room

A room with interior dimensions of a length of 9 m., a width of 3 m., and a height to ceiling of 2.65 m. was employed for the experiments. The room is a part of the laboratory building shown in Fig. 1(b). The south façade of the building comprises a glazed window that extends 0.85 m. from the floor by 1.8 m. to reach the ceiling. The glazing comprises a green tinted glass that is laminated with a clear glass. The green glass faces the exterior of the room. Visible and solar transmittances of the glazing are 0.67 and 0.26, respectively. All external facing walls are constructed from light weight concrete of 100 mm. thick and insulated with 50 mm. of polystyrene foam. Each of the shading slats seen in Fig. 1(b) has a width of 195 mm. and is spaced 300 mm. from each other. The interior of the room is painted pale grey. The reflectance values are: wall and floor 0.35, and ceiling 0.7.

3. Experiments of the Daylighting from the External Multiple Slats

The experiments conducted on 21st May 2010 and on 13th July 2010 will be described here. In the experimental room, illuminance sensors were placed on stands of height 0.75 m. from floor. The first stand was placed 1 m. from the window. Subsequent sensors were placed 1.5 m. from each other towards the back of the room. The last one was 8.5 m. from the window. Fig. 2 shows a photograph of the interior of the room.

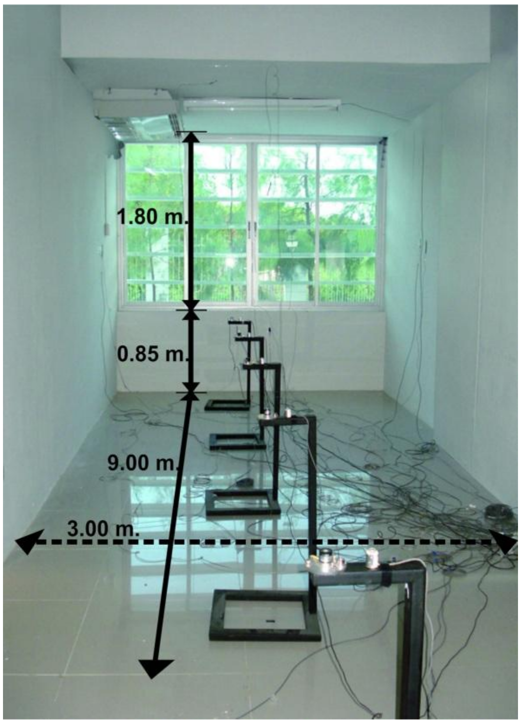


Fig. 2. The experimental room with illuminance sensors on stands.

A computer program was used to compute illuminance, temperature, and heat fluxes on walls. The computation results were to be compared with those from experimental measurements.

3.1. BESim Computer Program

A computer program called BESim was used in the calculation that required the measurement data from the station as its input. The program has been used for daylight and thermal calculations [13, 14]. The program requires defining the coordinates of each flat interior section in a zone. The program utilizes the method of Hien and Chirarattananon [15] in the calculation of view factors between all surfaces in each enclosed zone created by a user.

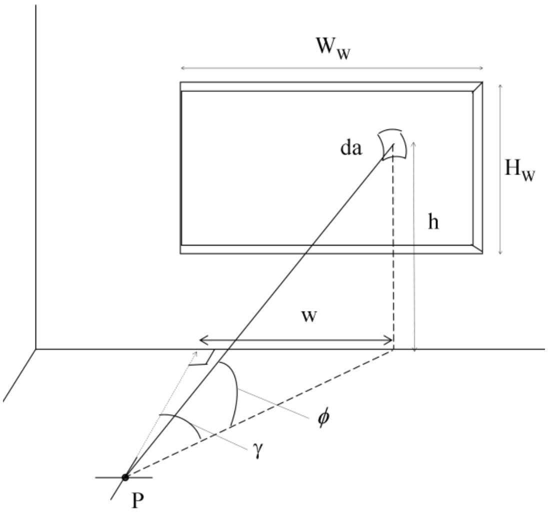


Fig. 3. Configuration of light flux contribution from a sky patch to a given point in the interior.

For daylight, BESim calculates sunlight illuminance and the effects of the shading devices using forward ray-tracing. For diffuse daylight from the sky, it uses flux transfer to calculate the inter-reflecting light. It uses configuration factors to calculate illuminance at a given point on a work plane. In the present version, BESim uses the ASRC-CIE sky luminance and sky irradiance models that utilize CIE clear and turbid clear sky models, partly cloudy and cloudy sky models [16]. Fig. 3 illustrates contribution of incremental illuminance to a point from daylight transmitted from an incremental sky patch through shading device and through window.

The incremental illuminance is expressed as

$$dE_k = \tau L(\gamma,\phi,\xi)\sin\phi\cos\phi d\phi d\gamma \qquad (1)$$

where dE_k is the incremental illuminance due to daylight from the sky patch transmitted through the window glazing. t is transmittance of window glazing. $L(\gamma,\phi,\xi)$is luminance of the sky at the given position. γ and ϕ are angles that relate the point and the position of the sky patch. And, ξ is angular distance between the sky patch and the sun.

BESim calculates dynamic heat transfer through a wall by the finite difference method and fully utilizes the principle of energy balance.

3.2. Experimental Measurements and Results

This section describes the results from experimental measurement and computer simulation on interior daylight illuminance. Two experiments were selected for the presentation.

Results of the Experiment on 23rd May 2010

During the experiment, the sun traveled northern, only daylight from the sky fell on the south-facing window of the experimental building. Fig. 4 exhibits the plot of beam normal (E_{vb}), diffuse horizontal (E_{vd}), and global (E_{vg})

daylight illuminance during 8:00-17:00 of the day. The sky was partly cloudy and the sun was fully obscured by passing cloud during 13:30-15:00.

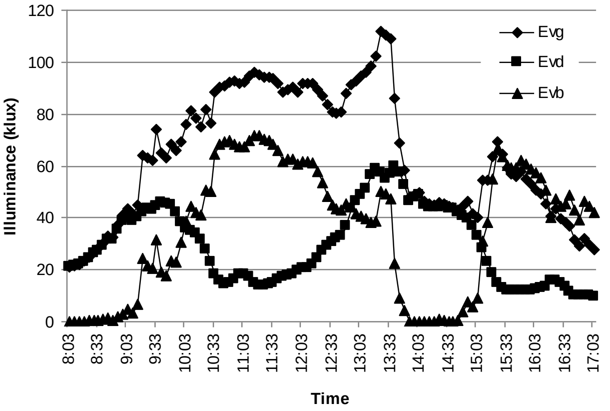
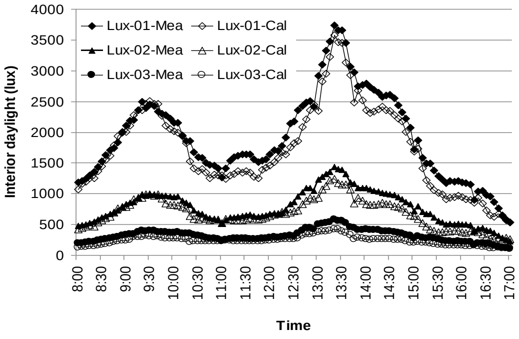
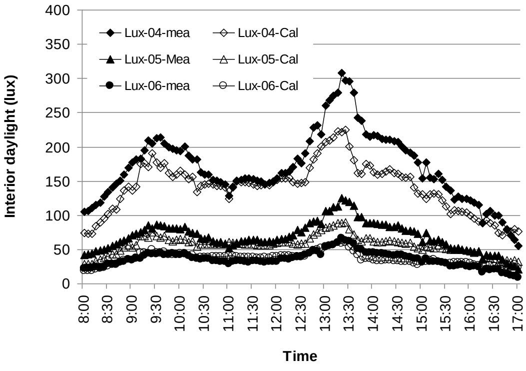


Fig. 4. Daylight illuminance from the station on 23/05/2010.

Measured daylight illuminances on work plane level in the test room are shown in Fig. 5(a) and 5(b). The figures show that illuminance at Point (Lux-01), at a distance of 1 m. from window varied close corresponding with the diffuse skylight. Even with low diffuse illuminance from the sky (about 15 klux), interior daylight levels at Points (Lux-05) and (Lux-06) reached 60 and 40 lux.



(a) Illuminance at Point 1-3.



(b) Illuminance at Point 4-6.

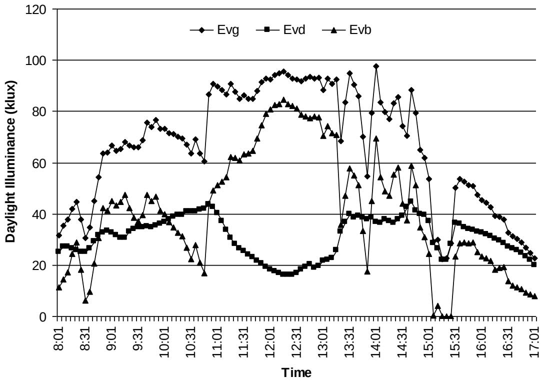
Fig. 5. Measured and calculated interior daylight for the experiment on 23/05/2010

The interior daylight illuminance calculated by BESim program were also exhibited on the same plots (Fig. 5(a) and 5(b)). The results match reasonably with those from the measurements.

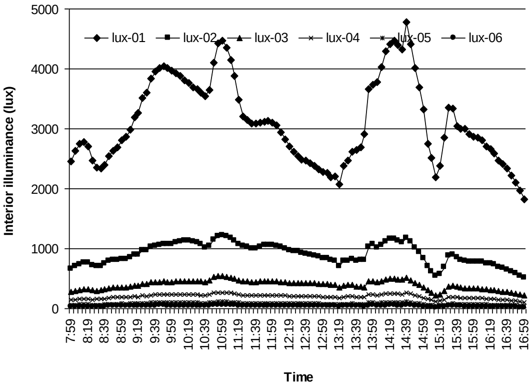
During the experiment, it was observed that the upper slats obscured the upper part of the sky for those locations close to the window. This would reduce daylight on locations closer to the window but has no effect on those further away from it. It was surmised that this would render a more uniform luminance of the overall scene in the room.

Results from the Experiment on 13th July 2010

On 13th July 2010, the experiment was performed for a non-shading case by removing the multiple slats from the window. As the sun moved further north, its radiation still did not enter the window. Fig. 6(a) shows plots of the measured global, diffuse and beam daylight illuminance on the experimental day. Fig. 6(b) shows the measured interior daylight illuminance at the six points.



(a) Daylight illuminance from the station.

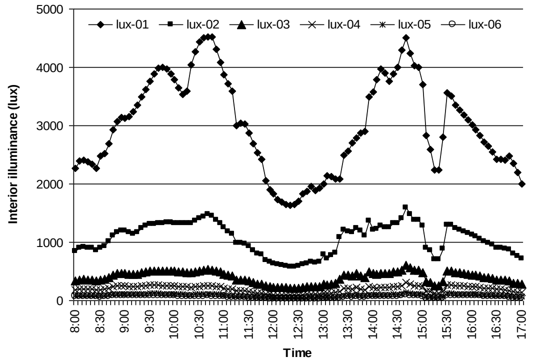


(b) Interior illuminance in the test room.

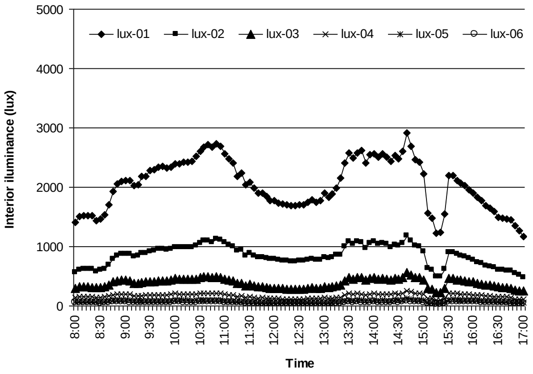
Fig. 6. Measurement of the daylight illuminance for the experiment on 13/07/2010

To simulate the daylight for this experiment, the BESim input file was modified by removing the slats from the window and then re-running. Fig. 7(a) shows a corresponding plot from the calculation which again exhibits reasonable agreement with the measurement.

An additional run was made by BESim in order to demonstrate the daylight effect from the external multiple slats. At this time, the input file with the slats was used again. Fig. 7(b) shows the graphs of the results of the new run.



(a) Window without the multiple slats.



(b) Window with the multiple slats.

Fig. 7. Calculated interior daylight in the test room for the experiment on 13/07/2010.

Two important observations can be gained from these results. The first is that illuminance values of the third or even the second measurement points (second and third line from the top) and deeper in Fig. 7(a) seem to be very similar in values and shapes to those in Fig.7(b) while the top line in Fig. 7(b) is just slightly more than half of those corresponding lines in Figs. 7(a). These results reinforce the statement made in the paragraph above.

The second observation is that the top line in Fig. 7(b) exhibit much less fluctuation than the corresponding line in Figs 6(b). At around 10:00 and at 14:00, the illuminance values for the point closest to the window reached over 4,500 lux in Figs 6(b) and 7(a), the corresponding values in Fig. 7(b) reached 2,750 lux. On the other hand, the smallest values from the point closest to the window in Figs 6(b) and 7(a) dropped to below 2,000 lux. The corresponding value in Fig. 7(b) was about 1,750 lux. This moderating effect of the multiple-slat shading device results from more effective shading of daylight from the upper part of the sky by the slats. The luminance in the upper part of the sky is higher than that of the lower part during cloudy and particularly during partly cloudy sky conditions. The higher daylight flux in the upper part of sky during partly cloudy sky is more effectively shaded by the upper slats.

4. Simulation Study of Daylighting Using External Multiple Slats

A room model with external multiple slats on a south-facing window was used in this simulation study. The room was assumed to be a part of a high-rise building in Bangkok. The model was also used to illustrate how to optimize energy benefit from daylighting with such configuration.

4.1. The Room Model

Figure 8 shows a perspective view of the interior of the room model. The room had a length from the windowed wall to the back of 20 m, and a width of 10m. This large room model allowed daylight to penetrate deep into the interior without the limit of room depth.

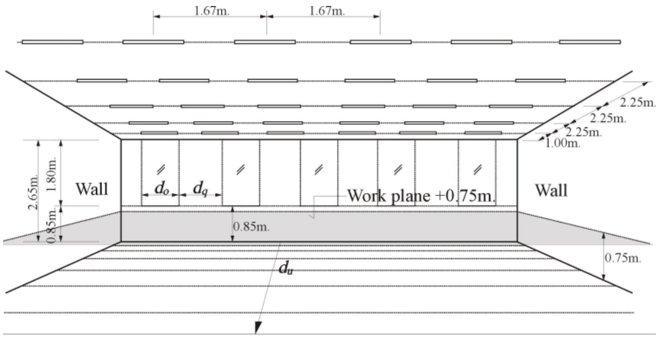


Fig. 8. A perspective view of the interior of the room model

The glazed window was located above the brick wall and extended to the ceiling. The height of walls and that of glazed windows were identical to those of the experimental room in Fig. 2. Standard fluorescent lamps, each requiring 36 W to produce 2,680 lumens, were to be used with standard magnetic ballasts, each ballast requiring 11 W, were installed on the ceiling. Six lamps spaced equally apart at 1.67 m form a row along the width of the room. Nine rows of such lamps were spaced 2.25 m. apart along the length of the room. Total numbers of lamp sets in the room were fifty four and the total electric power required when all were turned on was 2.54 kW. The reflectance values of the surfaces were: 0.7 for ceiling, 0.5 for walls, 0.3 for and floor. From BESim calculation, with verification from the simple lumen method, the lamps on the ceiling will illuminate the interior (without daylight) to 300 lux for general lighting. Each work station would have supplementary light for each lighting task required.

In the simulations that are being described, the heights of glazed window and of brick wall were adjusted so that the ratio of window area to total wall area (WWR) equals 0.0, 0.2, 0.4, and 0.68, respectively. At each WWR value, four types of glazing were examined.

Table 1 shows properties of the four types of glazing and wall components. Heat reflective glazing and low-E glazing are coated glasses. The glasses are all laminated as required by the building regulation in Thailand (since 2003) for buildings taller than 23 m.

The basic thickness of each glass layer is 6 mm. The width of the bonding layer is 0.38 mm, and the gas layer of the insulating glass unit (IGU) is 12 mm. The abbreviations used in the table are: GRN-CLR = laminated green (tinted) and clear, GRN-LE = laminated green and clear with low emissivity hard coat on the interior facing surface, GRN-IGU= green and IGU with low-emissivity coating on the surface of clear glass in the gap, HR-GRN = heat reflective green and green.

The room models with interspersing glass panes and opaque sections comprise a relatively large number of sections. This together with the use of six exterior shading slats per glass pane that require calculation of shading of beam radiation led to relatively long computation time for each set of input data. Therefore, only a set of hourly data of the 19th, 20th, and 21st of the months of March, June, September, and December of year 2000, together numbering 12 days, were used in the simulation runs.

Daylighting Scheme

It is recognized that daylight is highly variable, so daylight is planned to replace electric light near the windows. Daylight and electric light will jointly illuminate the room to 300 lux for general lighting during 8:00-17:00 hours. If daylight could provide illuminance of 150 lux or above at a borderline area for the duration of occupancy, the lamps in the row nearest to the area is expected to provide supplementary light flux to bring the total illuminance to 300 lux.

Table 1. Properties of wall and glazing

Type of material	Thickness (mm.)	Visible ray		Solar radiation		Solar heat gain coefficient	U-Value ($Wm^{-2}K$)
		Reflectance	Transmittance	Reflectance	Transmittance		
GRN-CLR	12.38	0.12	0.67	0.06	0.26	0.40	4.63
GRN-LE	12.38	0.14	0.63	0.09	0.19	0.27	2.68
GRN-IGU	30.38	0.16	0.55	0.24	0.16	0.22	2.57
HR-GRN	12.38	0.22	0.12	0.12	0.03	0.20	4.63
Concrete wall	100.00	NA		0.5	-	NA	3.00

The distance from windows to the borderline shown in Fig. 8 is called daylight penetration depth (d_u). The rows of lamps within the penetration depth an be switched off during the time of occupancy. As a part of this scheme, the number of rows of lamps beyond the penetration depth required will be determined from BESim calculation. The scheme used ensures that the lower limit of illuminance is not violated; it also does not set an upper limit on daylight illuminance. Results from the experiments have demonstrated that the shading configuration leads to moderation of interior daylight illuminance to acceptable uniformity. Dimming is also not required.

4.2. Simulation Results and Discussions

BESim was used to simulate the daylight distribution in the room model during normal office time of 8:00-17:00. The depth of penetration of daylight into the interior increased with the value of WWR (i.e. increasing size of window) and a larger accompanying heat gain. The relative gain of daylight and heat through the glazing and through the whole wall were related to the properties of each type of glazing, as well as the wall.

In each simulation run, BESim produced values of daylight illuminance on specified points on work plane level, values of heat flux from and temperature on each subsection of the wall of the room, and space cooling load. These results were used as described in the followings. The scheme of simulation and arrangement in this study comprises two steps

Step One: Determination of the daylight penetration depth and lighting arrangement

For a given value of WWR and a given type of glazing, BESim produced values of daylight illuminance on specified point(s) on the work plane. A sample plot of daylight illuminance for points at 1, 2, 3, …., 12 m from the window along a line near the middle of the room from 6:00-19:00 hour of 19 March for GRN-CLR glass and WWR of 0.2 is shown in Fig. 9.

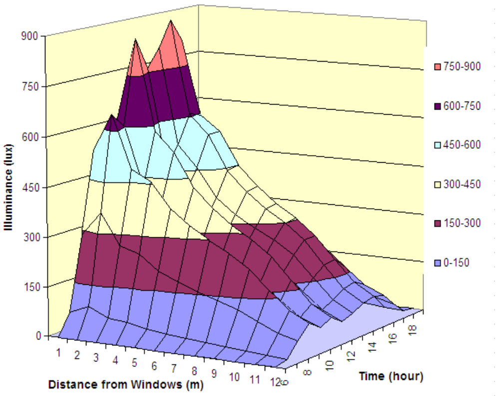


Fig. 9. Simulated daylight illuminance in the room for 19/03/2000.

The results from BESim calculation on interior daylight illuminance when each of the four glazing type, each of the three values of WWR, and each of the 12 days of simulation were examined to find daylight penetration depth during the office hours. As a part of this step, the number of rows of lamps required beyond the penetration depth were determined as shown in Table 2.

In cold and dry period (of 13 weeks), the day-length is shorter and it was assumed that an additional row of lamps may be required to be turned "on" for some days, or periods. The non-integral numbers in the table signify that the number of rows of lamps required may fall between the upper and the lower integral values. There were 39 weeks in other periods. If all lamps in the room were turned on for all working hours, electric energy required for a year is 5,939 kWh.

Step Two: Determination of savings of electric lighting energy and cooling energy

Table 3 shows savings of electric lighting from the simulation based on five office days per week.

Table 2. The penetration depth and rows of lamps required to be "turn on"

Glazing type	**DL depth and No. of rows**	**WWR**			
		0.00	**0.20**	**0.40**	**0.68**
GRN-CLR	DL depth (m)	0	7	11	12
	No. rows, W	9	6	4.5	4.5
	No. rows, O	9	5.5	4	4
GRN-LE	DL depth (m)	0	6	10.5	11.5
	No. rows, W	9	6.5	5	4.5
	No. rows, O	9	6	4.5	4
GRN-IGU	DL depth (m)	0	5.5	10	11
	No. rows, W	9	7	5	4.5
	No. rows, O	9	6.5	4.5	4
HR-GRN	DL depth (m)	0	0	1	2
	No. rows, W	9	9	9	8
	No. rows, O	9	9	9	8

Note: DL depth = daylight penetration depth,
No. rows, W = number of rows of electric lamps required to be "on" during winter period,
No. rows, O = number of rows of electric lamps required to be "on" during other periods.

Table 3. Electric lighting energy saved, cooling and total energy required

Glazing type	Item	WWR			
		0	0.2	0.4	0.68
GRN-CLR	Saving from lighting (kWh/year)	0	2227	3217	3217
	Energy for cooling (kWh/year)	3264	3157	3353	4141
	Total energy (kWh/year)	9203	6869	6075	6863
GRN-LE	Saving from lighting (kWh/year)	0	1897	2887	3217
	Energy for cooling (kWh/year)	3264	3151	3241	3729
	Total energy (kWh/year)	9203	7193	6293	6451
GRN-IGU	Saving from lighting (kWh/year)	0	1567	2887	3217
	Energy for cooling (kWh/year)	3264	3228	3174	3609
	Total energy (kWh/year)	9203	7600	6226	6331
HR-GRN	Saving from lighting (kWh/year)	0	0	0	247.5
	Energy for cooling (kWh/year)	3264	3887	4408	5056
	Total energy (kWh/year)	9203	9826	10347	10747

The number of rows of lamps supposed turned off were used to calculate savings of electric lighting energy. It was assumed that electric energy consumed by lamps contributed entirely to cooling load of the air-conditioner.

The ceiling and the walls on the eastern and western facades were insulated to an unrealistic level with glass fiber insulation of 1m. in thickness. Heat gain through the southern wall in Table 3 was calculated as the average daily value of load to cooling coil from the 12 days used in the simulation and then multiplied by the total number of working days in a year to obtain the annual value. The residual loads from heat gain through the ceiling and through walls on eastern and western facades were examined and were discounted from the load to the cooling coil. In the table, cooling energy is calculated from:

$$\text{Cooling energy} = \frac{\text{Heat through wall} + \text{electric lighting energy}}{COP} \tag{2}$$

COP stands for coefficient of performance of the air-conditioner. Here it was taken as 3.0. Higher cooling energy occurs in the cases where heat reflective glazing was used and was lowest for the case IGU glazing. Annual total energy in the table was calculated as the sum of cooling energy and electric lighting energy from the rows of lamps turned on.

Fig. 10 shows the pattern of variation of total energy with WWR corresponding to each wall configuration. The acronyms used for the labels are identical to those used in Table 2 and Table 3.

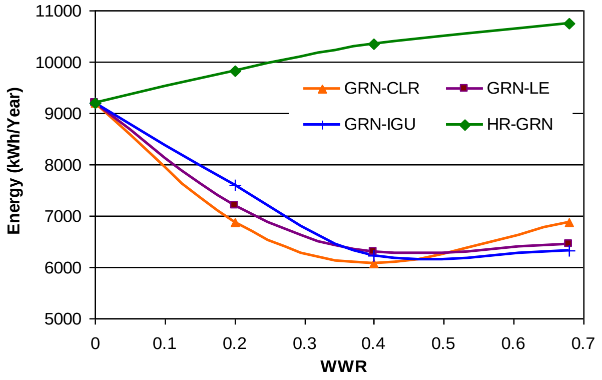


Fig. 10. Total energy plotted against WWR for each wall combination

Energy performances of walls with GRN-CLR, GRN-LE, and GRN-IGU types of glazing when daylighting was used in the scheme described are all clearly much superior to that of HR-GRN glazing. The striking common feature of the cases with the first three types of glazing is that total energy decline as the size of WWR increases from small values, where daylight penetrates deeper and is utilized to replace electric light. However, when the window size increases beyond a point, heat gain through window starts to overwhelm benefit from daylighting. For the cases where the first three types of glazing are used, there is a distinct point of minimum for each type.

5. Conclusion

The experimental results and the subsequent analyses demonstrate that the horizontal multiple-slat shading system performs well in terms of enabling daylight to be used to its full extent and at the same time limiting heat gain through window. The system can shade the direct sunlight effectively. It also limits daylight from certain portion of the sky to reach each part of the work plane at a range of distance from window. This leads to moderation of the daylight illuminance on the work plane near window and results in a more uniform daylight distribution along the distance from the window. The moderation of daylight in the space near window also enhances quality of lighting and reduces the potential of glare. The configuration allows viewing out from the interior with no perceptible sense of annoyance.

The BESim program could produce accurate results of daylight illuminance in the experimental room as well as results of heat gain into the room. The program was then employed to identify energy saving potential of the application of the shading configuration for daylighting application that leads to overall reduction of total energy used for both lighting and cooling. The results infer that there is an optimum size of window in relation to overall size of the wall.

Acknowledgements

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