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Daylighting for energy conservation in an existing building under tropical climate conditions: a case study of Lai Sue Thai building Ramkhamhaeng University

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Abstract

Daylighting using skylight has been shown to have a high potential in reducing electrical lighting energy, and could provide a more pleasant atmosphere of a daylit space. However, in hot climates, the main constraint of daylighting is the solar heat gain that contributes to major heat load for an air-conditioning system. If the balance between the beneficial light gain used to offset lighting energy requirement and heat gain from daylight is well considered, significant energy savings can be obtained. The main objective of the study is to evaluate the potential of daylighting for energy conservation in the tropics through theoretical analysis (simulation study) and experimental observation. Lai Sue Thai Building (an existing and educational building) located at Ramkhamkaeng University was selected as a case study. From analysis, use of daylight could reduce electrical energy in this building by up to 76% compared to the initial condition where fully lighting was supplied. Window orientation would also play an important role. Moreover, heat gain through windows due to daylighting can be controlled by overhangs and the appropriate Window-to-Wall ratio that would be about 30% for this building. An experimental study was also carried out to validate the results in a selected room. About 49% and 37% of Relative Root Mean Square Error (*RRMSE*) were observed in light and heat measurements, respectively.

Keywords: Daylighting, Fenestration, Tropics, Solar, Energy

1. Introduction

Solar energy can be an important alternative as a primary source of light and heat for commercial and residential buildings. As a major source of light, passive solar exploitation or daylighting can help reducing electric lighting requirements in buildings. In the tropics, daylighting through side window is the most common and the most effective method to bring daylight for illuminating the building interior [1]. In air-conditioned buildings, reduction of electric lighting also contributes to reduction of cooling load as electric lighting (responsible for 25 to 40% of the total electricity consumption) raises cooling load by 20% [2]. However, fluctuating sky conditions, climate, location, and orientation should be taken into architectural design considerations to take advantage and to control heat from daylight [3].

The potential of daylighting and daylighting systems have been assessed by some previous studies especially for locations in higher latitude areas [3-5]. As daylighting performance depends primarily on location and climate, appropriate window design in one location may not be valid in others. In this study, daylighting calculation procedure was then developed to evaluate the potential of daylighting namely daylight availability and the interplay between reduction in the requirement of electrical lighting and increase of cooling loads for possible energy savings under tropical sky and climate conditions on an annual basis. The electricity required for supplementary lighting and cooling were calculated and then compared to the initial condition where electric lighting was fully supplied to estimate the possible savings that can be achieved by daylighting. Lai Sue Thai Building (an existing and educational building) located at Ramkhamhaeng University, Bangkok, was selected as a case study due to high concern about energy conservation and pleasant atmosphere of this building.

2. Research methodology

Daylighting model (as shown in Figure 1) was developed to simulate daylight availability, electric lighting required for supplementary lighting, cooling load and energy required for cooling due to daylighting, and savings potential of the selected building. Experimental validation was then carried out.

2.1. Input data and reference building

Solar radiation and exterior illuminance on a horizontal surface of North Bangkok during work hours (8am – 5pm) measured by AIT meteorological station were adopted as

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meteorological data input in this study. Details are as shown in Figure 2 [6].

Lai Sue Thai building is a 5-stories concrete building with very large size overhangs (2.8 m in width) constructed at each story around the building which can effectively shade direct sunlight throughout the year. This building locates in Bangkok (13.9°N, 100.45°E) and consists of lecture rooms and office spaces. Interior surfaces of the building are painted white. Assuming the uniform spaces, the reflectance values of the ceiling, walls, and floor are 0.8, 0.8 and 0.6, respectively and surface properties of overhang are similar to those of building surfaces. Only one fenestration per room is placed lengthwise along the façade facing east, west, north, or south direction while other walls are opaque.

The Fenestrations are 6 mm-clear glazing, 1.5 m-high, and placed 1.65 m above floor level. Window-to-Wall ratio (the ratio of the transparent area on one façade and the overall façade area or *WWR*) of the rooms ranges from 43% to 56%.

Common configuration of window is as shown in Figure 3. It is noted that only rooms with a window exposing to exterior environment were taken into consideration
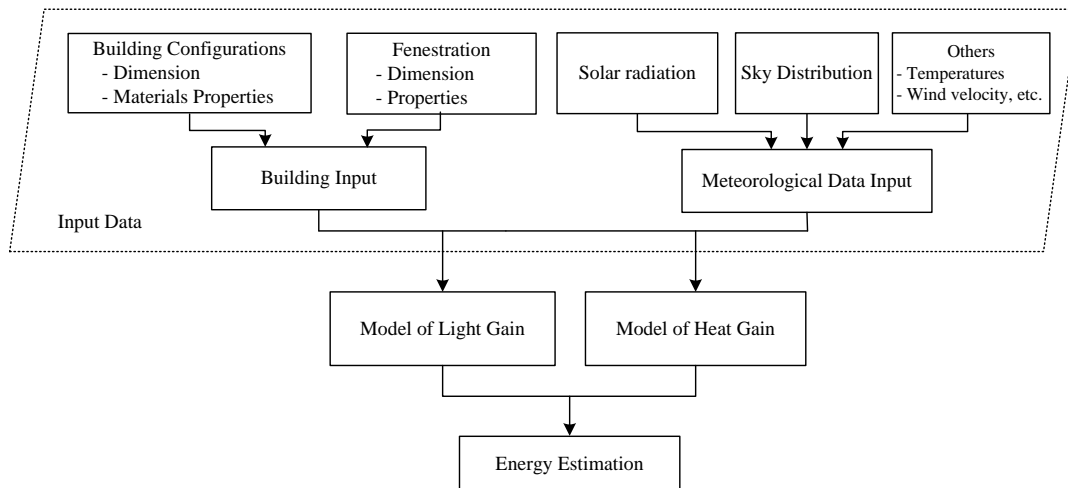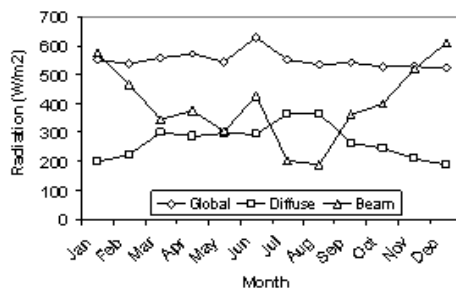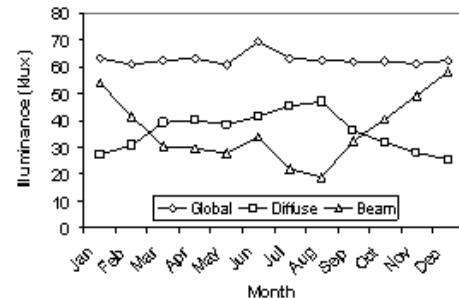

Figure 1 Flowchart of input data and calculation models

(a) Monthly average solar radiation

(b) Monthly average exterior illuminance

Figure 2 Exterior condition of Bangkok measured by AIT meteorological station
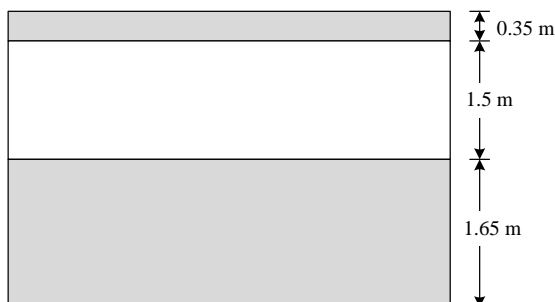 Tanachaikhan and Kumar (2012)

0.35 m

1.5 m

1.65 m

Figure 3 Common window configuration

2.2 Model of light gain

Model for light gain calculation is illustrated in Figure 4. The models of exterior daylight for tropical sky conditions are first determined and then followed by the calculation of daylight illuminance in the daylit space. The condition of the prevailing sky determines the amount of daylight available on a given location. The ASRC-CIE sky model [7] was found appropriate under tropical sky condition of Bangkok [8]. The diagram of light gain model is illustrated in Figure 5. Using the inputs, daylight components including sky, ground, and obstruction components are analyzed for direct and internally-reflected components of daylight illuminance. Direct component is dependent on sky, ground, and exterior obstruction. The reflected component is subject not only to direct component but also to daylit space geometry and interior surface reflectance.
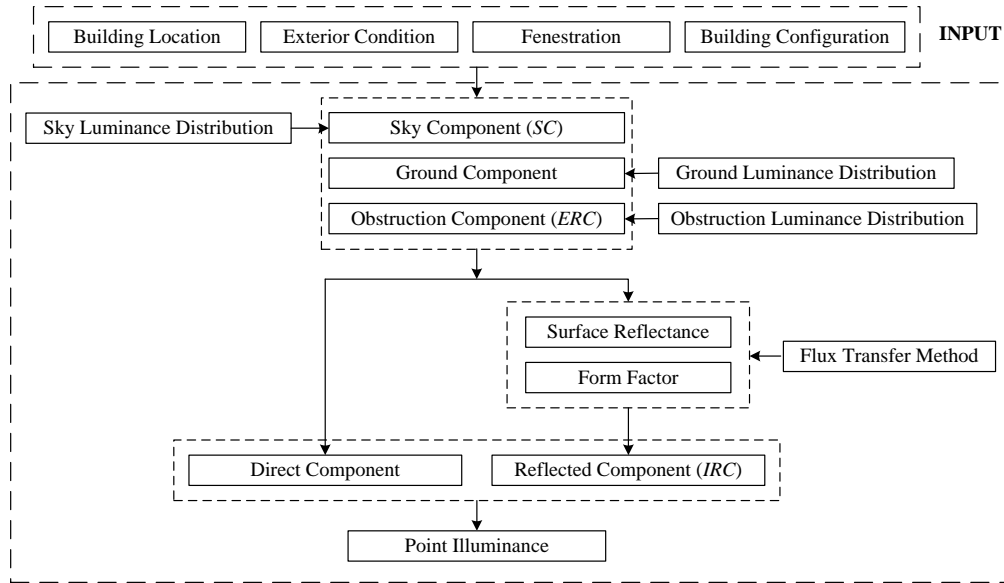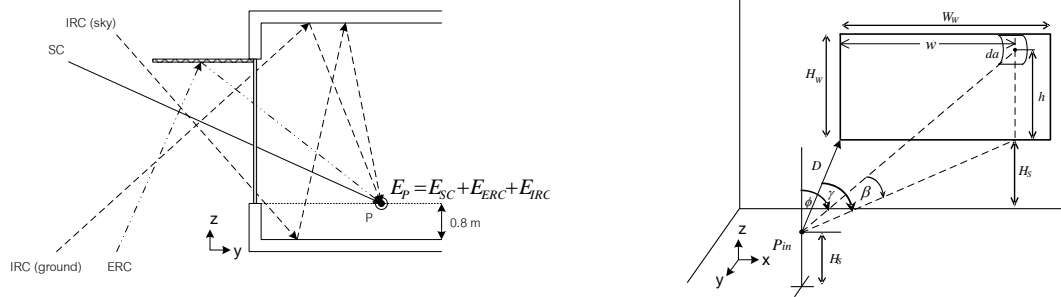
Figure 4 Model for light gain calculation

Figure 5 Components of daylight illuminance on work plane
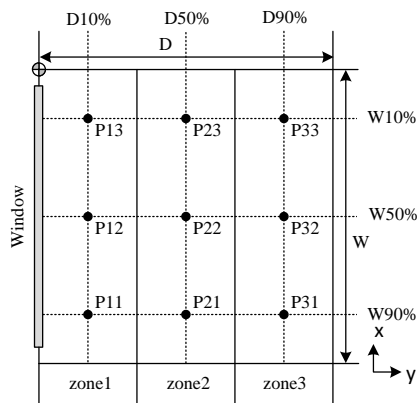

Figure 6 Plan view of the perimeter space

The diagram of daylight component on a given point P is presented in Figure 6. The three main light flux components of point illuminance on work plane are Sky Component (*SC*), Internally Reflected Component (*IRC*) (including skylight-reflected component and ground-reflected component), and Externally Reflected Component (*ERC*) from external or shading surface. To estimate these components, the window area was divided into small patches and the luminance of each patch was calculated, noting their dependence on the corresponding angles of azimuth (γ) and zenith (φ) which represents the geometrical relationships of

window patch and point P [2, 9] as shown in Figure 6. The daylight illuminance at point P (E_{Pin}) can be estimated as follows:

$$E_{Pin} = E_{SC} + E_{IRC} + E_{ERC} \tag{1}$$

where

$$E_{SC} = \iint_{\gamma\ \phi} \tau_{vis}(\theta) L_{SC}(\gamma,\phi)\sin\phi\cos\phi d\phi d\gamma \tag{2}$$

$$E_{ERC} = \iint_{\gamma\ \phi} \tau_{vis}(\theta) L_{ERC}\sin\phi\cos\phi d\phi d\gamma \tag{3}$$

$$E_{IRC} = \sum_{i=1}^{n}\left(E_{dxi} + \sum_{j=1}^{n}\rho_i F_{ij}E_{xj}\right)C_i \tag{4}$$

Normally, daylight illuminance is high only on the areas close to the window and drops exponentially for areas away from the window. Work plane (0.8 m above floor level) was therefore divided into three equal zones with different depths where D10%, D50% and D90% are the depths at 10%, 50%, and 90% of the room depth as shown in Figure 6.

The illuminance of nine different points on work plane was simulated every 15 minutes interval during work hours (8 am to 5 pm). Daylight availability and the supplementary electricity requirement were then estimated. Daylight Availability (f_i) or Cumulative frequency of daylight illuminance can be defined as the percentage of occurrence during a year when the hourly average illuminance of Point

i ($\bar{E}_{Pi}$) reaches a prescribed minimum illuminance ($\bar{E}_{Pi,\min}$) [10-1 1]. Daylight availability of zone i is then determined by:

$$f_i = \frac{\text{number of occurances } \bar{E}_{Pi} \geq \bar{E}_{Pi,\min}}{\text{total number of samples}} \times 100\% \quad (5)$$

In this study, the minimum requirement ($\bar{E}_{Pi,\min}$) was 500 lux based on the range of appropriate illuminance recommended by IESNA for an office with common tasks (200 – 500 lux) [9].

On – Off control method was applied in analysis assuming an electric lighting can be uniformly distributed from the ceiling at required Lighting Power Density ($LPD = 16$ W/m² [2, 12]) only for a particular zone area where daylight level was lower than the requirement. The annual average electric power required for supplementary lighting per unit floor area (PL (W/m²)) of a room with daylighting was then calculated by weighted-average method [9-11].

$$PL = LPD \sum_{i=1}^{3} \frac{(100 - f_i)}{100} A_i \bigg/ \sum_{i=1}^{3} A_i \quad (6)$$

2.3 Model to calculate heat gain

The heat balance method which consists of four distinct processes: exterior surface heat balance, wall conduction heat transfer, interior surface heat balance, and thermal radiation exchange between surfaces in a zone was adopted in the heat gain model as shown in Figure 7 and can be calculated by:

$$q_i = \tau_s(\theta)E_{t\theta} + q_{ri} + q_{ci} \quad (7)$$
where
$$q_{ri} = J_i - S_i \quad (8)$$
$$q_{ci} = h_{ci}\left(T_{gi} - T_i\right) \quad (9)$$

Therefore, the average heat gain through glazing per unit floor area (q_{gain}) is then given by:

$$q_{gain} = \frac{\left(q_i \times \text{glazing area}\right)}{\text{floor area}} \quad (10)$$

In this study, the interior heat source of the building was considered from lighting only as it is directly dependent on daylighting. Electric lighting (PL) distributes heat to be the load of air-conditioning system as the fraction of the coefficient of thermal power contribution to the load of air conditioning system by lighting ($C_l = 0.86$) [12]. Heat gain from electric lighting (q_{PL}) can be determined by:

$$q_{PL} = C_l \times PL \quad (11)$$

The condition of exterior air and internal heat sources determine the cooling load for an air-conditioned building. Since the penalty from daylighting is the major concern, cooling load due to daylighting (heat gain through glazing and heat dispersed from lighting) is mainly focused. The annual-average electric power for cooling per unit floor area (CL (W/m²)) and the total electric power demand for lighting and cooling per unit floor area were finally estimated as follows assuming Coefficient of Performance (COP) of the air conditioning system was 3.

$$CL = \frac{Cooling\ load}{COP} = \frac{q_{PL} + q_{gain}}{COP} \quad (12)$$

$$\text{Total} = PL + CL \quad (13)$$

3. Research results and discussion

Rooms with windows facing east, west, north, and south were assessed for average daylight availability. It is noted that no direct sunlight through opening space due to very large overhangs around this building. From Figure 8, the availability of daylight through façades facing east and west would be comparable similarly to those facing north and south which is influenced by sun path of this location. The highest availability can be observed for the opening on south façade while window facing north would exhibit slighter lower availability compared to those facing other directions. With very large transparent areas ($WWR \approx 50\%$), more than
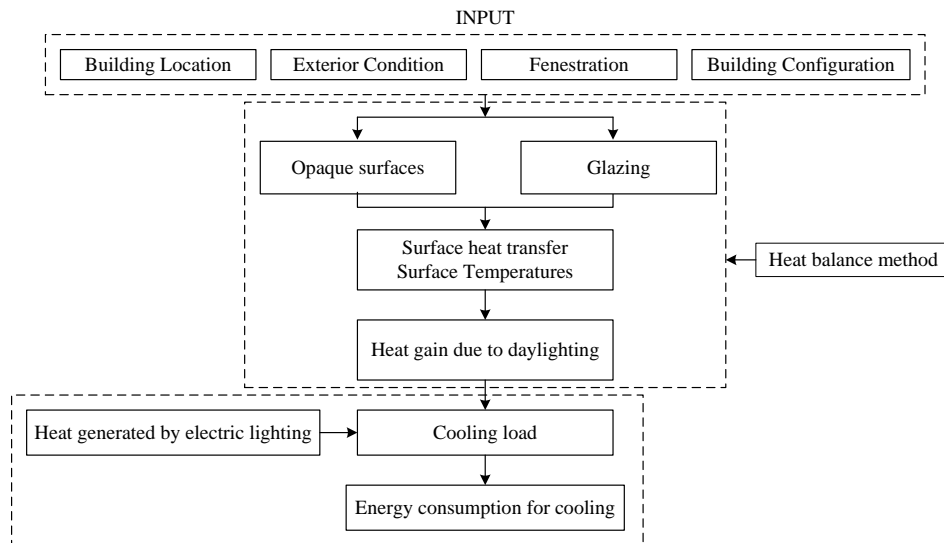
Figure 7 Calculation diagram of heat gain, cooling load, and energy consumption for cooling

90% of work hours can be sufficiently supplied by daylight in this building.

From Figure 9, fenestration facing south would exhibit the highest heat gain while that on north would provide the lowest value compared to other ones. These results agree well to previous studies on solar radiation in Thailand that relates to sun path of this location [2, 8].
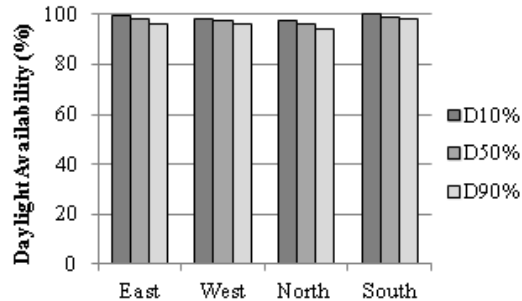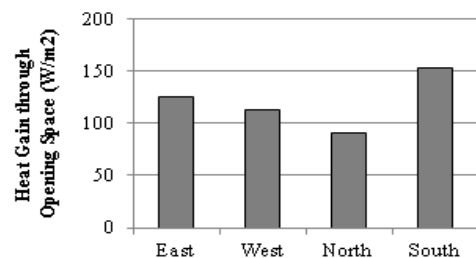

Figure 8 Average daylight availability

Figure 9 Average heat gain through space

Table 1 Comparison of electric power for lighting and cooling and the possible saving from daylighting through each window orientation

Orientation		Energy (W/m²)		%Saving
		FL-DL	SL-DL	
East	PL	16	0.3	98.1
	CL	14	9.6	31.4
	Total	30	9.9	67.0
West	PL	16	0.4	97.5
	CL	12.2	8.4	31.1
	Total	28.2	8.8	68.8
North	PL	16	0.7	95.6
	CL	9.7	5.4	44.4
	Total	25.7	6.1	76.3
South	PL	16	0.2	98.8
	CL	16.6	12.3	26.2
	Total	32.6	12.5	61.8

Note: *FL-DL* is fully lighting while allowing daylight
   *SL-DL* is daylighting with supplementary lighting

Table 1 shows the comparison of annual average energy demand for areas facing each orientation of two considered cases in Lai Sue Thai building. Due to high availability of daylight, reduction in electric lighting would be up to 98%. Also, more than 26% of energy for cooling can be saved as heat generated by electric lighting is reduced. Moreover,

significant energy saving can also be accomplished by up to 76% compared to the initial condition where electric lighting was fully supplied while allowing daylight.

From simulation, it can be also indicated that the appropriate *WWR* for this building should be about 30% for clear glazing windows to achieve the optimal savings. Use of high performance glazing, namely selective glazing (high visible transmittance and low solar transmittance), can also maintain the initial window size with up to 85% of saving. However, the renovation costs should be taken into consideration.

4. Experimental validation

Experiments were also set up to measure interior point illuminance and heat gain in a selected room for 5 days and the data were collected every 15 minutes interval. Point illuminance on work plane was measured at the center of the room. The parameters of heat components such as solar transmittance, surface and ambient temperatures, surface reflectance, and air velocity were separately measured and then analyzed for the total heat gain through glazing [11].
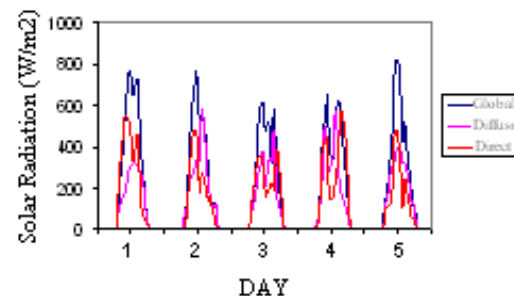
(a) Exterior conditions
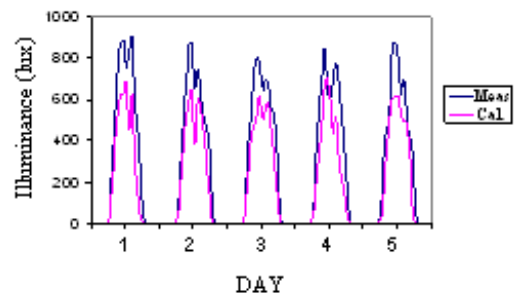
(b) Point Illuminance
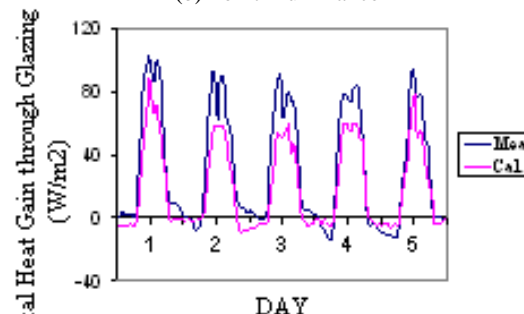
(c) Total heat gain through glazing

Note: *Meas.* refers to the measurement results
     Cal. refers to the calculation results

Figure 10 Comparison of experimental and calculation result

Comparison of calculation results (C_i) and experimental results (M_i) were performed by using Root Mean Square Error (*RMSE*) and Relative Root Mean Square Error (*RRMSE*) which can be expressed, respectively, by [12]:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}\left(M_i - C_i\right)^2}{N}} \qquad (14)$$

$$RRMSD = \frac{RMSD}{\overline{M}} \times 100\% \qquad (15)$$

Sky fluctuation and strong sunlight could play an important role in measurement of illuminance and heat gain. Also, the surroundings such as high rise building nearby and trees were not taken into calculation. From Figure 10, *RMSE* and *RRMSE* of point illuminance were about 132 lux and 49%, respectively. *RMSE* and *RRMSE* of heat gain were about 7.8 W/m^2 and 37%, respectively. Uncertainty of light and heat measurements due to instruments used were up to 2.3% and 1.7%, respectively using error propagation for analysis.

5. Conclusion

Daylighting model was developed for analysis of energy conservation under tropical climate conditions. Daylight availability, energy demand for lighting, cooling, and energy saving due to daylighting were assessed in annual basis for Lai Sue Thai Building as a case study. From simulation, daylighting potential in this building is high due to large transparent areas (approximately 50% of *WWR*) and heat gain can be controlled by overhangs. Daylight availability is greater than 90% that contributes to low requirement of supplementary lighting (up to 98% of saving in lighting). Also, lower heat load generated from electric light source could contribute to lower cooling load due to daylighting (up to 44% of saving in cooling). It can also noted that daylighting through north-facing window could provide up to 76% of overall electric saving compared to fully supplied lighting condition which is higher than savings from other window orientations. Moreover, the optimal saving can be achieved by use of the appropriate Window-to-Wall ratio (about 30% for this building). Experiments were also carried out to validate the model used. About 49% and 37% of *RRMSE* were observed in light and heat measurements, respectively. For further study, the influences of window configurations and shading devices would be performed.

6. Nomenclature

A_i	Area of zone i (m^2)
C_i	Configuration factor of interior surfaces and point P
E_{ERC}	Daylight illuminance from externally-reflected component (lux)
E_{IRC}	Daylight illuminance from internally-reflected component (lux)
E_{Pin}	Illuminance at a point P in zone i (lux)
E_{SC}	Daylight illuminance from sky component (lux)
E_{dxi}	Direct exitance from surface i (lux)
$E_{t\Theta}$	Total solar radiation on glazing (W/m^2)
E_{xj}	Direct exitance from surface j (lux)
F_{ij}	Form factor from surface i to j

h_{ci}	Heat transfer coefficient for air
J_i	Total radiosity of glazing surface (W/m^2)
L_g	Ground luminance (cd/m^2)
L_{SC}	Sky luminance from ASRC-CIE (cd/m^2)
L_{ERC}	Obstruction surface luminance (cd/m^2)
q_{ci}	Heat convection (W/m^2)
q_{gain}	Solar heat gain through glazing (W/m^2)
q_i	Total heat gain through glazing (W/m^2)
q_{ri}	Thermal radiation (W/m^2)
q_{PL}	Heat gain due to electric lighting (W/m^2)
S_i	Total thermal radiation received from other surfaces (W/m^2)
T_{gi}	Glass temperature (Kelvin)
T_i	Temperature of room ambient (Kelvin)
Total	Total energy demand due to daylighting (W/m^2)
φ	Corresponding zenith angle from point P to sky patch da (degree)
θ	Angle of incidence (degree)
γ	Corresponding azimuth angle from point P to sky patch da (degree)
τ_s	Solar transmittance
τ_{vis}	Visible transmittance

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9. Appendix

9.1 Form factor and configuration factor

The form factor (F_{ij}) in equation (3) is a geometrical relationship between surfaces i and j, representing the fraction of flux received by surface j emitted from surface i as follows [9]:

$$F_{ij} = \frac{1}{\pi A_i} \int\limits_{A_i} \int\limits_{A_j} \frac{\cos\theta_i \cos\theta_j}{D^2} \, dA_i dA_j$$

Configuration factor (C_i) in equation (3) is a geometrical relationship between point i and surface j, representing the fraction of flux received by point i emitted from surface j as follows [9]:

$$C_i = \frac{1}{\pi} \int\limits_{A_j} \frac{\cos\theta_i \cos\theta_j}{D^2} \, dA_j$$
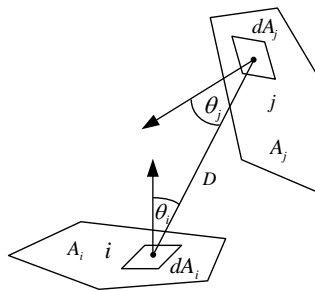
Figure A Geometrical positions between i and j

9.2 Clear glazing properties

Properties	Values
Solar/Visible transmittance	0.8/0.88
Solar/Visible reflectance	0.07
Front /Back emittance	0.84
U-Value (W/m^{2}K)	5.83
Shading Coefficient	0.96