CHAPTER 3

METHODOLOGY

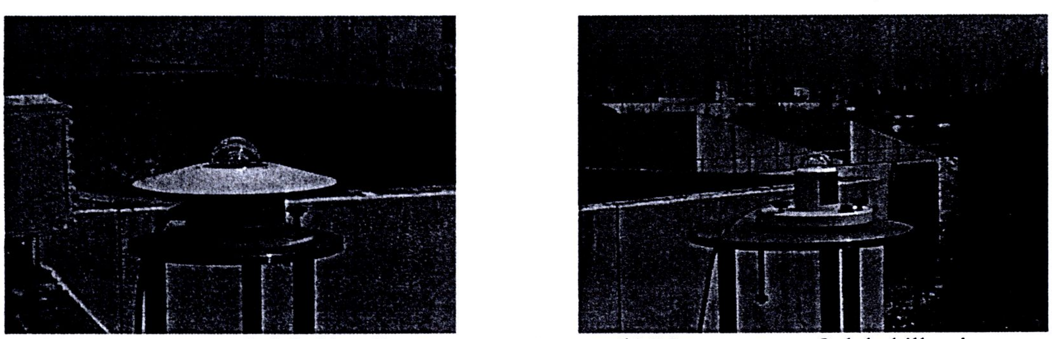
This chapter presents the steps of appraisal and modeling for efficacy of daylight in tropical climates. Solar irradiance and daylight illuminance acquired from two meteorological stations located in the outskirts of Bangkok were employed to characterize the daylight efficacy. Statistically The data from the two stations were also employed to investigate correlations between the efficacy and insolation parameters i.e. Perez's clearness index, brightness index and solar altitude. Various models compiled in Chapter 2 were evaluated against the measured data in order to evaluate their performance. In this study, a new model was also developed empirically for tropical daylight efficacy. The technical details for the daylight station are given in this chapter as well.

3.1 Daylight Measurement Stations and the Observed Data

In this study, two data sets of daylight illuminance and solar irradiance were employed for the investigation of tropical daylight efficacy. The first data set was gathered from a station located in the northern area, approximately 40 km north of the center of Bangkok. The data bank provides five-year data collected during the years 1999-2004.

The station itself is on the roof deck of a two-storey building of Energy Field of Study, School of Environment, Resources and Development (SERD), Asian Institute of Technology (AIT). No tall building or structure offers obstruction. The station is at latitude 14.7°N and longitude 100.6°E. This research station records data on both daylight and solar availability consistent with CIE standards. A number of sensors were installed at the station to measure of irradiance and illuminance in a tropical climate. These sensors are used to measure different kind of climate properties as summarized in table below. Table 3.1 indicates more than 20 types of data recorded and sensor models and names of the equipment suppliers.

All the data measured at the station were recorded at one-minute intervals except for the sky luminance and radiance data, which were recorded at fifteen-minute intervals. The measurements were routinely performed during 5:30-19:30, local time. The data spans from sunrise to sunset. Figure 3.1 exhibits a concurrent measurement of global illuminance and global irradiance at the station.



(a) Measurement of global irradiance (b) Measurement of global illuminance

Figure 3.1: Measurement of global irradiance and illuminance at the AIT station

Table 3.1: Summary of measured quantities and sensors used

Measured Data	Sensor Model	Supplier
Irradiance		
Direct beam	NIP	EPLAB
Global-horizontal	PSP	EPLAB
Diffuse-horizontal	CM11	Kipp&Zonen
Global-vertical (NESW)	SBP-801	Eko
Illuminance		
Direct beam	ML-010SD1	Eko
Global-horizontal	ML-010S	Eko
Diffuse-horizontal	ML-010S	Eko
Global-vertical (NESW)	ML-010S	Eko
Luminance		
145 Points of sky vault	MS-300LR	Eko
Zenith	ML-010SZ	Eko
Other meteorological data		
Atmospheric turbidity	MS-110	Eko
Temperature	HMP45A	Vaisala
Humidity	HMP45A	Vaisala
Infrared radiation	CM11	Kipp&Zonen
Global radiation at 15 altitude	PSP	EPLAB

To establish a valid set of measurements, the one-minute data were first verified in accordance with the IDMP quality assurance procedure. The validated data were then archived in 5-minute formatted database. The above procedure was routinely undertaken at the monitoring station. Only records passing the quality control test were further examined.

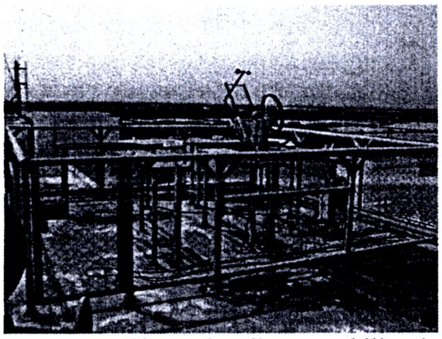
In the step of processing of data, Table 3.2 lists the set of data required in the analysis and modeling of luminous efficacy of global, diffuse and beam components. The following data were taken from more than 20 measurements at the station.

Table 3.2: Measurement and documentation selected for the analysis and model development of luminous efficacy

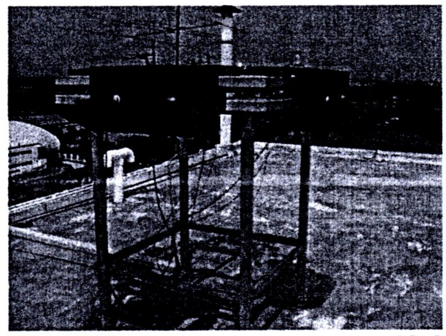
Description	Type of Data
Site identification	• Latitude (degree) • Longitude (degree) • Site elevation (m)
Date	• Julian date • Year
Local standard time	• Hour • Minute
Data selected for the analysis and model development of luminous efficacy	• Global irradiance/illuminance • Diffuse horizontal irradiance/illuminance • Direct normal irradiance/illuminance

The other set of radiation data was taken from a station located in the south of Bangkok. The station is managed and operated by the Joint Graduate School of Energy and Environment (JGSEE).

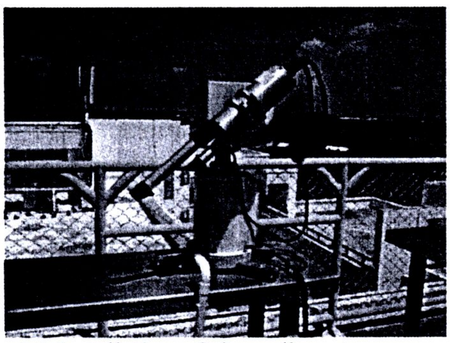
The station was erected in 2009 on a roof deck of a seven-floor building of the school of Bioresources and Technology at KMUTT, Bangkhuntien campus. Most of the sensors and equipments of this station were actually transferred from the AIT station. A sky radiometer is a new instrument being installed in the station. The data processing procedure of the JGSEE station is identical to that of AIT station. Figure 3.2 illustrates some photographs of the equipment installed at the JGSEE daylight station.



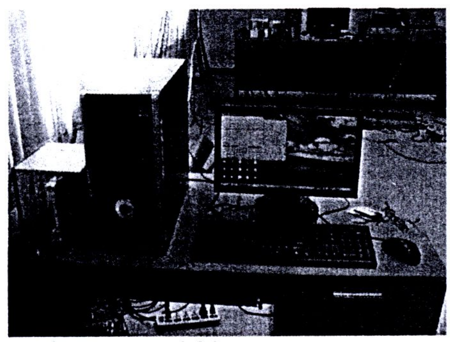
(a) Measurement of beam irradiance and illuminance



(b) Irradiance/illuminance measurement on N, S, E, W



(c) Installation of sky radiometer



(d) Data acquisition system

Figure 3.2: Installation of equipment at the JGSEE station

3.2 Assessment and Characterization of Daylight Efficacy

Research activities in this part aimed to evaluate the magnitude of the global, diffuse horizontal and beam normal efficacy of daylight in a tropical climate. The time dependencies and seasonal variations of the daylight efficacy are expected to be observed.

To achieve the mentioned purposes, the hourly mean values and the standard deviation of the efficacy were derived statistically from the validated five-minute records for the twelve calendar months. A well-known software named SPSS was employed for this work, because the one-year data from the JGSEE station was incomplete, this process was performed only for those of the AIT station.

3.3 Modeling of Daylight Efficacy

In modeling tropical daylight efficacy, the efficacy was plotted first as function of three insolation parameters: clearness index, brightness index and sun geometry (Solar zenith angle). Such variations help determine the functional form of the proposed models.

Various efficacy models published internationally and described in Chapter 2 were evaluated against the tropical data to assess the accuracy of their prediction. The model performances were evaluated at first with their own original coefficient values. The models were next fitted with the tropical data to obtain their local coefficient values.

Performance evaluation was then made again with the local coefficient that the results would indicate the most suitable form of the model for tropical daylight efficacy.

This study pays particular attention to the model proposed by Perez. This model includes complete parameters that would be expected to characterize better the variations of tropical daylight efficacy. The basic inputs of the model are Perez's clearness index, brightness index and solar zenith angle. The function form of the proposed model will be expressed as:

$$Ev = Ee \times F(insolation\ conditions\ /\ solar\ geometry) \quad \text{Equation 3.1}$$

where

$F(\varepsilon, \phi_s, \Delta) = a_i(\varepsilon) + b_i(\varepsilon) f(\phi_s) + c_i(\varepsilon) g(\Delta)$,
Ev = daylight illuminance, lux,
Ee = solar irradiance, W/m^2.

For model derivation, the term of the function F specified above were obtained in each case through least-square fitting of large data set representative of a variation of modeled quantities in a year.

The function F of luminous efficacy takes the following parameter into consideration which are: the sky clearness (ε), the sky brightness (Δ) and the solar position (ϕ_s).

The models were evaluated on the basis of statistical deviation tests. The statistical estimators of *Root Mean Square Difference* (RMSD) and *Mean Bias Difference* (MBD) are common model deviation estimators that were used to evaluate the accuracy of the models.

The two estimators are different in nature and can give different results. It is therefore necessary to report the two estimators for each of the compared models. The RMSD gives more weight to points far away from the mean, and results in only positive values. The MBD can give positive or negative values, corresponding to that positive value which implies an overestimation of the model.

Typically, solar irradiance papers utilize absolute values as statistical estimators. This study evaluates the relative values to obtain comparable results.

The definition of root mean square difference (RMSD) is exhibited by the following expression:

$$RMSD = \sqrt{\frac{\sum_{i=1}^{N}(C_i - M_i)^2}{N}} . \quad \text{Equation 3.2}$$

Similarly to the above, definition of the Mean Bias Difference (MBD) and Relative Mean Bias Difference (RMBD) can be expressed by the following equation:

$$MBD = \frac{\sum_{i=1}^{N}(C_i - M_i)}{N}.$$ Equation 3.3

The study in this part was carried out separately for the data obtained from the AIT station and those obtained from the JGSEE station. In reference to Table 3.2, the lists defined of selected data require for simulation and the number needed to analyze is 12 data.

Table 3.3 summarizes and describes the technical details of relevant solar radiation and daylight measurement instruments. The main equipment associated with this study are the Pyheliometer, Pyranometer and Light meter. The Pyheliometer is used to measure the beam irradiation while the global and diffuse irradiation on the horizontal surface is undertaken by the Pyranometer. However, diffuse horizontal would be observed by placing a shadow band over the Pyranometer, the adjustment of which is required periodically. In the case of illuminance, measurements are taken by Light Meter model number ML-010S.

Table 3.3: Summary of measured quantities and sensors used at JGSEE station

Measured Data	Sensor Specification
Direct irradiance Pyheliometer Model: NIP Supplier: EPLAB	Linearity: $\pm$0.5 % from 0 to 2800 W.m^{-2} Subtending angle: 5° 43' 30" Time response: 1 second (1/e signal) Temperature dependence: $\pm$1 % over ambient temperature range
Global irradiance Pyranometer Model: PSP Supplier: EPLAB	Linearity: +0.5% from 0 to 2800 W.m^{-2} Temperature dependence: +1% over ambient temperature range-20 to + 40°C Time response: 1 second (1/e signal) Cosine error: +1% from 0 to 70° zenith angle:80° zenith angle Receiver: coated with Parsons' black optical lacquer Orientation: no effect on instrument performance
Diffuse-horizontal irradiance Pyranometer Model: CM11 Supplier: Kipp&Zonen	Linearity: 0.0% in the range of 0-500 W/m^2 and 0.7% at 1000 W/m2 Temperature dependence: + 1% over ambient temperature range10 to + 40°C Cosine error: less than 3% at 10° sun altitude Time respond: less than 5 second (1/e), 99% value after 24 s Spectral range: 305-2800 nm. (50% transmission points) Material: Anodized Aluminium *Shadow Band Stand* - model SBS (Kipp & Zonen) : Material: Anodized aluminium Height: 800 mm Ring outer diameter: 620 mm Ring width: 55 mm Ring width/ring radius ratio: 0.185 Mounting base diameter: 280 mm
Total-vertical (NESW) irradiance Pyranometer Model: SBP-801 Supplier: Eko	Linearity: 0.3% (in the range of 0 to 1 kW.m-2) Wavelength region: 300-2800 nm. Accuracy: +1.5% (at 0.25 kW.m-2or more) Cosine error: 2% (when the zenith angle is 0° to 80°) Temperature dependence: 1% (at -20°c to +40°c) Time response : Approx. 2.5 sec. (1/e signal) Azimuthal error: 2% (when the zenith angle is 75°)

Table 3.3: (Continued).

Measured Data	Sensor Specification
Direct illuminance Light meter Model: ML-010SD1 Supplier: Eko	Measuring range: 0-200,000 lux Full opening view angle: 5° ±0.2° Slope angle: 1° ±0.2° Temp. dependence: ±1.0% (-20 to +50°C)
Illuminance *Global* *Diffuse-horizontal* *Total-vertical (NESW)* Light meter Model: ML-010S Supplier: Eko	Measuring range: 0 to 200,000 lx Cosine response at 30/60/80: 2/7/25 % Temperature dependence: 1 % (at 50°C band)
Zenith luminance Luminance meter Model: ML-010SZ Supplier: Eko	Measuring range: 0-30,000cd Temp. dependence: ±1.0% (-20 to +50°C) Full view angle: 11°
Temperature Temperature sensor Model: HMP45A Supplier: Vaisala	Measurement range: -32.9 to 60 C Output scale: -40 to 60 C equal 0-1 VDC Accuracy at 20 C: ±0.2 C Temperature sensor: Pt 1000 IEC 751 1/3 class B
Humidity Humidity sensor Model: HMP45A Supplier: Vaisala	Measurement range: 0.8-100 %RH Output scale: 0-100 %RH equal 0-1 VDC Typical long term stability: better than 1% RH per year Temperature dependence: ±0.05%RH/C Response time (90%) at 20 C: 15 s with membrance filter Humidity sensor: HUMICAP 180
Atmospheric turbidity Turbidity sensor Model: MS-110 Supplier: Eko	Incident part: Full view angle: 2.5° Slope angle: 0.8° Window: Quarts glass Aiming: By means of pin-hole Spectral system (Interference filters): Wavelength: 368±2nm, 500±2nm, 675±2nm, 778±2nm Half band width: less than 5 nm 1/10 band width: less than 20 nm Transmission: Approx. more than 20% Detecting part: Sensor: Silicone pin-photodiode Temperature coefficient: less than -0.1 %/°c Linearity: less than 1.0 % Temperature control system: Temperature control accuracy: 40°c ± 1°c Control temperature: 40°c (at air temp. 25°c or less)
145 Points of sky luminance Sky scanner Model: MS-300LR Supplier: Eko	Range of measurement: Luminance: 0-50 kcd/m^2 (full scale) Approx. 15 cd/m^2 (resolution) Radiance (0.3-3.0μm): 0-300 w/m^2.sr (full scale) Approx. 1.0 w/m^2.sr (resolution) Scanning time: About 4 min. 30 sec. for total 145 points for both radiance and luminance Scanning procedure: Stepwise (Sequences of measurement are shown in measuring points diagram) Drive unit: Pulse motor Reducing mechanics: Reduction ratio : Azimuth 1/60 Zenith 1/50

	Resolution: Azimuth 0.03° Zenith 0.036° Accuracy of pointing: 0.2° Luminance sensor: Full view angle: 11° Slope angle: 1° V Mismatch: 2.5% UV-Blocking: 0.2% (for full scale) IR-Blocking: 0.2% (for full scale) Temp. Coefficient: 0.1%/°C (with compensation circuit) Linearity: 0.3% Radiance Sensor: Full view angle: 11° Slope angle: 1° Linearlity: 0.5% Temperature coefficient: -0.1%/°C