An Integrative Approach for Indoor Environment Quality Assessment of Large Glazed Air-conditioned Airport Terminal in the Tropics
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AN INTEGRATIVE APPROACH for INDOOR ENVIRONMENT QUALITY ASSESSMENT of LARGE GLAZED AIR-CONDITIONED AIRPORT TERMINAL in the TROPICS

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Abstract

The indoor environment quality in large glazed space such as airport terminals affects its users in many ways. The indoor environment quality assessment of such a building was typically conducted objective measurement using measurement and subjective assessment using questionnaire survey. However, limited resources and measurement period imply that would be incomplete and cannot provide accurate results. Computer modelling is thus an additional tool in the integrative approach for indoor environment quality assessment and analysis to improve its comfort and energy performance.

Field measurement on the objective variables defined the environment quality and energy consumption, as well as questionnaire survey on the subjective judgment defined the indoor comfort. While the computer modelling was assessed across the air temperature, indoor glazed roof surface temperatures, mean radiant temperatures, operative temperatures and illuminance, to examine the building energy performance across the annual cooling load in 2010.

The inner surface temperature over glazed roof were recorded as 56°C due to high level solar penetration, even when the indoor air temperatures over the floor level remain stable within the standard comfort zone. This rose the mean radiant temperature and was considered as main cause for indoor discomfort revealed by the survey. The survey found the employees to be slightly uncomfortable and dissatisfied, particularly in summer. The total energy consumption in 2010 was very high compared against the energy benchmarking. This study confirms that the large proportion of glazed roof is the cause for both overheating and thermal discomfort even with excessive use of the cooling system. In addition, recommendation was made to improve the thermal comfort condition in the large glazed air-conditioned terminal.

Keywords: Large glazed space, airport terminal, questionnaire, field measurement, thermal comfort, dynamic thermal model, lighting model and lighting quality.

1. INTRODUCTION

Airport terminals provide passengers with access from ground transportation to board aircrafts, as well as processing disembark from their aircrafts. These buildings are characterized by large open spaces and high ceilings. Often, for brightness and openness, glazed panels are used extensively for the construction of transparent roofs and walls in most of these buildings, regardless of cultural and climate context [1]. Thermal environment in such spaces are poor due to solar penetration and high radiant temperature [2]. Glazed buildings are notoriously uncomfortable regardless of a huge, complicated, high running cost and maintenance cooling system, especially in hot-humid climates [3]. This is thus indicated that the high probability of thermal discomfort in these glazed buildings.

Recent research and practices show that a quality and comfortable interior space of a proper design is closely associated with work efficiency and productivity of the occupants inside the building. The indoor environment consists of many elements which influence building users [4]. There is an increasing concern over the quality of buildings’ indoor environments study, particularly in hot climates where air-conditioning is essential [5].

In order to assess such buildings, an integrative approach assessment would be explored due to the dynamic interaction of subsystems in buildings such as building geometry, indoor environment and occupants needs [6]. The indoor environment assessment can be applied with various levels of input information to support the type of evaluation and level of detail needed to meet the aim of an individual study. A standard method is to use objective measurement to investigate the existing conditions and overall indoor physical variables, and subjective assessment using a questionnaire-base survey to obtain occupants’ feedbacks on their personal response to the indoor environment [7]. As the energy use for cooling in a
tropical climate is often the largest portion in such buildings, utility bills would be analysed over a period of time to assess energy performance [8]. Large airport energy consumption can be as much as energy consumption by a city, thus any improving energy efficiency in airports can result in huge energy savings [9].

Due to the complexity of the building geometries, together with the limited resources and measurement period, computer modelling thus used for overall assessment of annual indoor environment quality and energy performance. In order to increase the accuracy of the thermal and lighting simulations, it is necessary to calibrate these models by comparisons with the measured results for critical variables, the indoor temperatures, the total average cooling loads and illuminance [10].

The occupants are a major factor in comfort definition within airports. They are the passengers, airport officers, airline operators, security personnel and shop attendants. The passengers and their escorts occupy spaces for a short time, so drift in temperature might not have any noticeable effect on them. The officers and staff groups work for long periods within the terminals, and so the building is expected to provide the necessary indoor environments that will ensure, rather than detract from, those individuals’ efficiency and productivity [9].

In recent years, a number of thermal assessment studies have analysed the results of occupant feedback surveys in large glazed airport [11; 12; 13]. However, there is no single study that has investigated response from the offices and staff groups at Suvarnabhumi Airport, Thailand, to use their qualitative feedback regarding their experience and combined with predicted computer simulation results within a particular airport.

Thus this study aims to establish a method that assesses both the indoor environment quality and energy performance in the building using both objective and subjective assessment and integrating computer modelling.

2. METHODOLOGY

The indoor environment being assessed was at the main passenger lounge of Suvarnabhumi Airport Terminal in Thailand, characterised by a tropical climate, using an integrated method: objective measurement for quantitative data, subjective assessment for qualitative variables and computer modelling for annually predicted indoor environment energy performance analysis.

Objective measurements in the study were confined to air temperatures, indoor glazed roof surface temperature, relative humidity and illuminance. For subjective assessment, a questionnaire survey was administrated to the officers and staff groups to determine their own thermal and visual experiences and investigate their perception of the degree of comfort offered in this passenger lounge. The dynamic thermal and lighting models were created and run under the weather data files from the local meteorological stations over the same selected periods as the field measurements. The representative models were used to predict indoor physical environment conditions and energy performance. Results from the physical measurements and subjective assessment were analysed and compared with the recommended operative temperatures for international airport thermal comfort bands in summer of the CIBSE [14] &ASHRAE [15] and work plane illuminance standard [16]. The energy data were prepared from airport facility management record and assessed by comparing against the average international airport energy intensity benchmark.

2.1 The building

Suvarnabhumi Airport was designed by American architect, Helmut Jahn. The building is located at 13°40’ north and 100°44’ east close to Thai’s capital, Bangkok. The Airport is the sixth busiest airport in Asia and is the sixteenth busiest in the world [17]. As the largest in the country, the airport serves both domestic and international passengers, with a total useable area of around 563,000 m². The single passenger terminal building is 111 m. in width, 444 m. in length, 6 floors and 2 basements and faces north, with a useable area of around 140,000 m² (Fig. 1). The main space examined in this study, the lounge is on the 4th Floor, where comprise of the domestic and international departures, airline check-in counters, airport international Counters and other services.

The dimensional construction data were collected from the architect’s firm. The construction of the facades of the terminal building is mainly 12 mm. thick laminated tempered glasses with supporting steel trusses, while the terminal roof made of strips of insulated metal sandwich panels facing south and steel framed toughened single glazing panels with 12 mm. thick low-e coating. The ground floor and intermediate floors are of 23 cm thick precast concrete with finishing.

2.2 Weather data
Thailand is considered to have a tropical climate, with high temperatures and high humidity levels throughout the year. Meteorological statistics show that summer in the capital area is between March and June, while the hottest month is April and May with the highest daily maximum temperature at 38.5°C. Average maximum air temperature is 30.0°C. Winter is between November and February with daily minimum temperature at 20.0°C. The daily minimum is reached between 0500h−0700h and the maximum 1200h−1600h. The time of daily maximum and minimum seldom varies by more than an hour throughout the year. A fairly rapid rise in temperature take place during the first six or seven hours of daylight and after reaching the maximum the temperature falls gradually in late afternoon and slowly throughout the night.

The annual average relative humidity is 71.9%. The 24 hours mean relative humidity varies significantly in the range of from 42−94%. The highest radiation received is in the month of March when most places experience a dry season and the sky is generally clear during the day and at night. The average daily range for March is 7.0 kWh m^−2 (Fig.2) [18].

A full year of weather data for 2012 was collected from the local weather station of the meteorological office for the purpose of calibrating the computer model. The data set includes the hourly figures of the seven variables: the global and diffused solar radiation, air temperature, relative humidity, cloudiness, wind speed and direction. This set of weather data was used in thermal modelling to predict the indoor environment and the annual energy consumption.

2.3 Field measurements and equipment used

Measurement of indoor air temperatures over a longer period is important to study the thermal behaviours particularly associated with unwanted thermal stratification and overheating problems within the airport terminal building. Thus additional data was gathered by using site measurement carried out for twenty consecutive days from 12th September to 1st October 2012 for the purpose of calibrating the computer thermal model including the air temperatures and glazed roof surface temperatures.

- Temperature and humidity measurement was done by Squirrel Grant SQ2010 data loggers (±1%). The measured data can be recorded and transferred to a PC by Squirrel View software. The air temperatures were measured simultaneously over six locations from the 4th, 5th and 6th floors in the departure lounge, all from 2.0 m. above the floor. The other temperatures were recorded in the 6th floor ceiling, underneath the transparent roof and the transparent roof surface (Fig. 2a and 2b). The humidity was also measured in the 6th floor.

- Out of the twenty day measuring period, the measured result on the 12th September 2012 represented a clear hot day; the 28th September 2012 represented an overcast hot day. The data from these two days were used in the calibration of the thermal model.

- The measurement of visual comfort parameter was done with a lux metre (TES 1330) with an accuracy ±3% for illuminance factors. Lighting measurements were carried out on an overcast sky day, the 28th September 2012. The illuminance was measured every 2.0 m. between check-in counters at the walkways; between counter check-in positions on the passenger lounge floor and outdoors at one single location and moment in time.

- Outdoor temperature and weather data were collected from the local weather station in the airport of the meteorological office.

The measurement and monitoring should be carried out in summer in order to provide a clearer picture of the indoor thermal environmental performance of the building [19]. However, due to the greatly restricted airport security process, the field study scheduled for hot days in summer was deferred to hot rainy days.

2.4 Energy consumption in the airport

Energy use for cooling in a tropical climate is the largest area of use on a national level. The best way to determine energy consumption is to analyze utility bills over a period of time, as part of the energy assessment of a building [20].

Air-conditioning at Suvarnabhumi Airport Terminal building is based on a chilled water cooling system. According to the cool water supplier agency report (District Cooling System and Power Plant Ltd) in 2011, the amounts of chilled water to cooling coil for air-conditioning system in the airport are summarized in Table 1. In 2010, the total cooling load was 3.11x10^6 kWh and the total other electricity consumption was 3.27 x10^6 kWh giving the total energy consumption at 6.38 x10^6 kWh in Suvarnabhumi Airport [21].

2.5 Subjective Assessment- Questionnaire Surveys
The questionnaire survey was conducted at the same time as the physical measurements for 20 days in the passenger lounge of Suvarnabhumi Airport. The questionnaire used in this paper was a modified version of the one used in the ‘Thermal Comfort Study of an Air-conditioned Lecture Theatre in the Tropics’ [5]; the modifications designed to make it more applicable to the airport passenger lounge environment. Thus the questionnaire survey consisted of three categories: respondent demographics, the level of satisfaction in each season and the respondents’ perceptions of the thermal sensation and impressions of comfort (Appendix A).

- The respondents’ demographics were collected including gender, age, nationality, occupation, working period, activity levels (metabolism) and type of clothing [22].
- Respondents were asked to rate the level of satisfaction in each season and score their perception within a four-point preference scale;
- The assessment of the thermal and visual environment was based on the occupants’ vote on the thermal and lighting sensation, humidity and air movement in the departure lounge using the seven-point ASHRAE sensation scale [15].

In 2011, Suvarnabhumi Airport had a total number of 7,626 personnel which are permanence employee 2,568 personnel and outsourced workers approximately 5,058 personnel (197%). Suvarnabhumi Airport accommodated 100 scheduled airlines, 88 of which were mixed passenger-cargo airlines, and 12 of which were pure cargo airlines [23]. Assume that each airline provides 10 employees for 24 hours service. The airlines thus have an approximate additional total number of 1,000 personnel. In addition, there are other agencies’ employees such as, the Customs Department, Police Station, Thailand Post Company, etc. around 200 personnel. The airport would have the airport officers and staffs group around 8,826 personnel all together.

The process used to select the sample was a random sampling. The sample size for the members of staffs in the airport departure lounge was calculated based on Yamane’s equation as following [24].

\[
n = \frac{N}{1 + Ne^2}
\]

where: \( n \) is the sampling number;
\( N \) is the statistic population;
\( e \) is allowable error ratio.

According to approximated population in the airport, the calculated sample size would need to be 383 with a confidence coefficient of 95%, and with an error of 5%. In the study, the questionnaires were presented to the 700 airport officers and staff groups working in the passenger lounge (300 airline operators, 300 airport officers and 100 other agency and shop attendants). 383 responses (54%) were obtained.

After gathering the questionnaires, the survey data will be keyed in Excel file before transferring to the Statistical Package for the Social Sciences program (SPSS) for the occupants’ responses analyze. It included the calculation of mean values, frequency distributions and correlation between independent factors.

2.6 Dynamic thermal modelling

To create representative dynamic thermal simulation models, the study was carried out in three stages. It begins with creating the airport terminal building model using dynamic thermal modelling tools and assigning building elements and indoor conditions. Then, the dynamic thermal models were divided into multi-zone and run under the weather data files from the local meteorological stations over the same selected periods as the field measurements. Finally, the predicted results were compared against the measured ones. For the dynamic thermal model calibrations, comparisons were made for two critical variables, the indoor temperatures and the total average cooling loads within the airport terminal building on the hottest clear and on overcast days.

For large glazed buildings, assigning a large single zone or dividing each level into one zone may not be sufficient to correctly model the spaces. To provide a more accurate analysis, a multi-zoned model is recommended. They treat each space within a building as a zone, calculate the heat and air movement among these zones through energy mass balance equations and predict dynamic thermal performance of a building. Hence they are often used for overall thermal performance and energy consumption of a specific design [25].

A dynamic thermal models of the Terminal building was created using Tas. It included the arrival lounge (ground floor), departure lounge (4th floor) and the long-span glazed roof and walls were the major feature of the model (Fig. 3). The indoor conditions such as temperature in air-conditioned units were derived from the building mangers, while heat gains from occupants, lighting and equipment were set to the CIBSE Guide A value (Table 2) [14]. In addition, the building
elements such as floor, wall, glazed roof and construction were specified from the software construction database with reference to architectural specifications from designers and contractors (Table 3).

2.7 Overview of dynamic thermal and lighting simulation programs

Nowadays there are many thermal and lighting simulation programs available. There are some difference approaches in each program. Tas 9.2.1 was used for the prediction of the thermal due to this version cannot simulate lighting environment performance, so Dialux 4.1 was used for the prediction of visual performance within Suvarnabhumi Airport Terminal. Therefore, it is important to carefully consider how these programs simulate the heat and lighting within the buildings.

2.7.1 Overview of Tas application

Dynamic thermal simulation software: Tas is a complete solution for the thermal simulation of a building, and a powerful design tool in the optimization of a building’s environmental, energy and comfort performance [26]. It utilizes proven and accurate empirical methods for estimating convective heat transfer from internal surfaces [27]. Therefore, the Tas simulation software is chosen because it provides an effective, realistic and comprehensive virtual environment in which the thermal and energy responses of any building may be accurately modelled. The main applications of the software are in assessment of environmental performance, prediction of energy consumption, plant sizing and analysis of energy conservation. The movement of heat in various forms is conveyed into, out of and around the building by heat transfer [28].

- **Conduction** is treated dynamically using a method derived from the ASHRAE response factor technique. This efficient computational procedure calculates conductive heat flows at the building elements and surface of wall as functions of the temperature histories at those surfaces.
- **Convection** is treated using a combination of empirical and theoretical relationships relating convective heat flow to temperature difference, surface orientation and, in the case of external convection, wind speed.
- **Radiation** exchange is modelled using the Stefan-Boltzmann law, using surface emissivity from the materials database. Long-wave radiation from the sky and the ground is treated using empirical relationships. Solar radiation absorbed, reflected and transmitted by each element of the building is calculated from solar data on the weather file. The calculation entails resolving the radiation into direct and diffuse components and calculating the incident fluxes using knowledge of sun position and empirical models of sky radiation. Solar absorption, reflection and transmission are all calculated from the thermo physical properties of the building elements. External shading and the tracking of sun patches around room surfaces may be included at the user's option.
- **Air movement** is taken account for each zone by latent gains, moisture transfer and the operation of humidification and dehumidification plant.

2.7.2 Overview of lighting simulated applications

A number of lighting software programs such as Lightscape, Radiance and Dialux are available, each of which requires different input characteristics and provides various outputs. Acosta et al. examined five light simulation software programs and established that the illuminance levels reached with the Dialux are acceptable results [29]. Therefore, it was selected to assess the visual performance in this study, because these software programs have been used widely in building researches.

Dialux is available as free software and is currently used by many designers and light planner worldwide. It is simple, effective and professional; also providing the latest 86 luminaire data from the world’s leading manufacturers. Dialux relies on CAD data and can be exported easily.

The standard assessment of daylight quality is based on an interpretation of the measured data as presented in Table 4 [16].

2.8 Thermal comfort criteria for the tropics

The operative temperature combines the simply air temperature and the mean temperature, which is the average surface temperature of the surrounding walls, into a single value to express their effect. The operative temperature is the most useful indicator of thermal comfort in buildings.
The CIBSE Guide A recommended the operative temperature of comfort criteria for air conditioned passenger lounge in any airport terminals between 22°C to 24°C [14], while, the ASHRAE Standard 55 gave the operative temperature of thermal comfort as 23°C to 26°C in the range 40–70 % RH is generally acceptable [15].

There are a number of thermal comfort studies done in hot-humid climate countries, results of the studies indicate that people in hot-humid climates are acclimatized much higher temperature of comfort levels [30; 31]. Therefore adopting the CIBSE standard for indoor comfort conditions may lead to overcooling and energy waste for hot-humid climates. The recommended operative temperatures for international thermal comfort criteria of The ASHRAE Standard 55 were chosen in this study.

3. RESULTS and DISCUSSIONS

The results are presented in six sections. The first are the collected from the site measurement. The second and third describes the calibration and simulation results. The fourth presents cooling load compared against the energy benchmarking. The fifth covers the results of the questionnaire survey. The sixth describes the comparisons based on the model predictions of the indoor environmental variable with both empirical and subjective studies in the case study approach.

3.1 Field Measurement Results:
There were various meteorological conditions during the monitoring sessions: clear hot days and overcast hot days mixed with intermittent showers. Results from 15th to 16th September 2012 and 28th September 2012 represented three overcast hot days and the rest were clear hot days.

(a) The air temperature and relative humidity
It appears that the indoor thermal environment of the departure lounge floor area was not significantly affected by the external weather conditions, due largely to the fact that this area is air-conditioned and also another factors such as; the roof heights and the size of the space.

During both hot clear and overcast days, the external air temperatures were between 24°C and 35°C, while the indoor air temperature over the twenty days marginally swung between 21.8°C and 26.9°C within the departure lounge floor. The higher indoor air temperatures normally occurred between 1200h to about 1700h, after the outdoor temperature had reached its peaks. The indoor air temperatures considerably remained within the adaptive thermal comfort range (Fig.4).

The indoor thermal environment over the 6th floor was affected by the outside conditions. The daily air temperatures ranged between 24.6°C to 35.4°C, even though it was cooled with air-conditioning. Solar radiation greatly influenced the glazed roof surface temperature and heat arising from the stratification of air within the building affects the upper level most. The air temperatures gradually started to rise during the afternoon. At that time the highest glazed roof surface temperature recorded was 66.9°C, which occurred on 23rd September at 1300h. These surface temperatures fluctuated between 25.5–66.9°C. Around midday for 4–5 hours, the temperature was over 40°C. These high surface temperatures were exacerbated by direct radiation from above and convection from the heated air rising from below. The resulting high operative temperature within the terminal did lead to some overheating and thermal discomfort, particularly in the upper floor as experienced in other similar locations in highly glazed buildings [32].

In general, during both hot/clear days and hot/overcast days particularly in the afternoon from 1200h to 1700h, it clearly shows that the temperature stratification is clearly evidenced below the glazed roof over a passenger lounge, as the indoor top floor temperatures considerably exceeded the external air temperatures causing the thermal condition on the top floor to be extremely hot, especially from early to late afternoon.

The measurements revealed that the indoor air temperature in the occupied zones was not affected by the external weather conditions, but maintained between 21.8°C and 26.9°C. This range was within the adaptive thermal comfort criteria between 23°C and 26°C, suggested by ASHRAE standard 55 [15].

Apart from the indoor temperature, relative humidity is another major comfort variable. It was also measured in the occupied zone. It ranged 40–70 % was recommended as standard indoor condition [15]. Average relative humidity on the passenger lounge floor was within 43.7 % and 63.0 %. The mean relative humidity was 55.0 %. The mean value of relative humidity was within the same recommended standard.

(b) Indoor Lighting Condition
Fig. 5 illustrates the resulting measured illuminance over the passenger lounge floor. The outdoor lighting standard was based on the critical illumination 5,000 lux specified. Throughout the measurements, the range of illuminance from the ground floor departure lounge was between 119–522 lux. Only 18.8% could be shown to have an adequate level of daylight according to the standard assessment of daylight quality [16]. Since the terminal roof was designed in a saw tooth form, with metal sheet roofs facing south and glazed roofs facing north, a large quantity of daylight can enter from the northern aspect of the transparent roofs. The natural light then only benefits some areas underneath the airport’s transparent long-span glazed roof.

3.2 Dynamic thermal and lighting calibration results

A set of 2012 weather data consisting of hourly values of seven weather variables: the direct and indirect solar irradiation, air temperatures, relative humidity, cloudiness, wind speed and direction was used as the representative year data in both the dynamic thermal and lighting models. In order to improve the accuracy of the thermal and lighting simulations, the calibration of the two models were carried out as follows:

- The representative dynamic thermal model was run for twenty consecutive days from 12th September to 1st October 2012;
- The calculation results of the thermal models were compared with the measured one for two critical variables: the glazed roof surface temperatures and the total average cooling loads within the long-span glazed roof over large air-conditioned glazed terminal of Suvarnabhumi Airport on the hottest clear day and overcast day. Illuminance from the lighting model was compared with the measured one on the selected overcast days;
- For the average indoor air temperature comparison, the average daily predicted glazed roof surface temperatures were compared against the measured ones;
- For the profiles of temperature comparison, 12th September 2012 was chosen to represent a clear hot day and on 28th September 2012 to represent an overcast hot day to use in the calibration;

For simulating the lighting conditions, 28th September 2012 was chosen to represent an overcast hot day using in the calibration; the building blocks were used as domestic and international departure lounge. For the internal condition, the air temperatures for all air-conditioned zones were set according to recommended comfort criteria for airport terminals by CIBSE Guide A [14].

3.2.1 Dynamic thermal model calibration

Although this passenger lounge was air-conditioned, solar radiation had greatly influenced the indoor thermal condition due to the transparent roof. It could heat easily the glazed roof panels and other surfaces that exposed the penetrating sunlight.

The environment variable used to calibrate the thermal model for this space was the inner surface temperatures of the transparent roof. Since the indoor thermal condition within the large glazed air-conditioned terminal was contributed by the heat transfer in internal building material surfaces from convection and long-wave radiation exchange and solar heat gain from solar radiation from the transparent building components. Both the average inner transparent roof temperature and the inner transparent roof temperature profiles on hot clear and overcast days of the predicted were also compared against the measured ones.

(a) The average daily surface temperature calibration

In order to calibrate thermal model, the inner transparent roof temperatures were the main outputs being measured from the model and compared with measured surface temperatures.

The main factor to contributed thermal condition in large glazed terminals is due to solar heat gain from solar radiation entering from the transparent component, especially the glazed roof. The high surface temperature that leads to high radiation heat to the space was considered to be the main cause for the negative effects on the thermal comfort resulting in more energy consumption from the air-conditioning system.

Table 5 shows the comparison between average measured temperature and average Tas predicted temperature by date. The average external temperature was 28.01°C. The average measured glazed surface temperatures increased by 29.18–38.34°C. Similarly the Tas predicted average glazed surface temperature increased by 27.90–38.99°C. There were differences between predicted results by Tas and measured results. It was found that Tas calculations tend to be underestimated comparing to that of the measurement from 0.44–5.00% (Average 2.07%). The main reasons for these
differences were due to the fixed internal conditions in the Tas model which were based on general assumptions, while the real internal conditions were irregular. Moreover, there were also numerous infiltration airflow paths which allowed the internal heat to be dissipated in the real building, while infiltration rates were fixed in the Tas model.

This sensitivity test also confirms that the created 3D Tas model is capable of accurately modelling thermal stratification within the passenger lounge and thus can be used to model in the next step.

(b) Calibration on clear hot day and overcast hot day

On a clear hot day, the average surface temperature difference between the predicted and measured was around 2.7°C. The average difference on a hot overcast day was smaller. Over all the average measured temperatures are higher than the predicted, which mean the modelling results could be slightly under estimated (Fig. 6a and 6b).

3.2.2 Lighting model calibration

The indoor lighting condition can be examined by using Dialux 4.11 which is the software that has been developed in order to simulate and analyse both indoor and outdoor lighting performance.

The results of model calibration were calculated in the form of the illuminance. Measured data was obtained in the check-in lounges between check-in counters on a overcast day of 28th September 2012 at 1300h-1400h when the external illuminance was 5,000 lux. The measurement was carried out at 9 x 23 points and compared with computer simulation model results. The computer model was set in the same date at 14:00. The artificial lightings for the model was set according to the actual building: 637 sets of halogen roof light (637x1000 W), 420 sets of check-in counter fluorescent light (420x58 W) and 220 sets of PLC canopy light (220x32 W).

The illuminance distribution predicted by the lighting model followed fairly well with the measured ones. The minimum illuminance different from measurement and simulation was 0.57 and 0.73 % respectively. The maximum illuminance different from measurement and simulation was 1.74 and 2.75 % respectively. An overall agreement between the average measured and simulated illuminance was good, even though there were a few points where the predictions were different from the measured ones, especially points that were close to the glazed wall to the north [33].

Fig.7 reveals that the average relative deviation on the departure lounge was less than 5 %, while the poorest was closed to the glazed wall to the north. The daylight model was then accepted for assessment in this study.

3.3 Predicted indoor environment results

Basically, the interest of this study was to examine the inner vertical temperatures within a large glazed air-conditioned airport terminal. Therefore, the central passenger lounge in the dynamic thermal model was further divided for each floor to capture the differences in thermal condition in this space. At the roof level, a separate zone was created between the transparent glazed roof and the ceiling. Such a division was intended to differentiate subtle changes in temperature from one place to another; data which was used to compare with those from the base model at the same positions. The central passenger lounge in the lighting model was divided into 207 zones between check-in counters for ground floor to capture the differences in lighting conditions in this space.

3.3.1 Predicted indoor thermal environment results

The occupant’s comfort in an indoor physical environment was considered in both thermal and visual environment aspects. The formal was assessed by the air temperature, which affect convective heat exchange between the occupant and its surrounding, the surface temperature of all surfaces that the person can see, mean radiant temperature, which determines radiation heat exchange. Often the operative temperature is used to combine both part of heat exchanges, including air movement [34]. The visual was assessed by the illuminance.

In the thermal modelling, the meteorological weather data on 1st May 2012 was used to represent a clear summer day and that on 3rd May 2012 was used as an overcast summer day. Similarly that on 26th December 2012 was used as a clear winter day and 7th December 2012, an overcast winter day.

(a) Inner surface temperature

During the hottest period in summer, the highest outdoor temperature was 38.0°C on a clear day and 34.5°C on a overcast day. The inner glazed surface temperatures reached a peak of 55.7°C on a clear day and 43.5°C on a overcast day, respectively (Fig.8a and 8b).
During the hottest period in winter, the highest outdoor temperature was 30.7°C on a clear day and 32.3°C on a overcast day. The inner glazed surface temperatures reached a peak of 38.6°C on a clear day and 39.3°C on a overcast day, respectively (Fig.8c and 8d).

(b) Mean radiant temperature

The surface temperature greatly affected the mean radiant temperature (MRT) on both the ground floor passenger lounge and the top floor level. The MRT also took into account the view factors of these surfaces. Two locations were considered: one on the ground floor passenger lounge and the other on the top floor ceiling.

Around the midday of summer, solar penetrated through the surfaces around the ground floor passenger lounge and raised MRT up to 32.0°C on a clear day and to 30.7°C on a overcast day. On the top floor ceiling, MRT reached a peak of 47.2°C on a clear day and 39.4°C on a overcast day (Fig.9a and 9b).

Around the midday of winter, solar energy penetrated through the surfaces of the passenger lounge, causing the MRT to rise to a 29.1°C on both clear and overcast days. On the top floor ceiling, the highest MRT was 39.2°C on both clear and overcast days (Fig.9c and 9d).

(c) Air temperature

Solar radiation had greatly influenced the air temperatures on the top floor ceiling, so this location received specific attention.

During the hottest hour of summer, the air temperature on the top floor ceiling peaked at 38.9°C on a clear day and 35.8°C on an overcast day (Fig.10a and 10b).

During the hottest hour of winter, the predicted highest air temperature on the top floor ceiling was 31.9°C on a clear day and 32.6°C on a overcast day (Fig.10c and 10d).

(d) Operative temperature

Operative temperature describes the average of air temperature; mean radiant temperature (MRT) is the most useful indicator of thermal comfort in buildings. The operative temperatures of 22-26°C are widely considered acceptable for an airport departure lounge, as recommended by ASHRAE [15].

In summer, the highest predicted operative temperature in the passenger lounge was around 28.3°C on both clear and overcast days. The highest predicted operative temperature on the top floor ceiling was 29.7°C on a clear day and 29.1°C on a overcast day (Fig.11a and 11b).

In winter, the highest operative temperature on the passenger lounge was around 28.4°C on both clear and overcast days. The highest operative temperature on the top floor ceiling was 30.0°C on a clear day and 28.7°C on a overcast day (Fig.11c and 11d).

3.3.2 Predicted indoor visual environment results

In summer, the average illuminance of the passenger lounge was 373.7 lux on clear day and 351.1 lux on an overcast day. In winter, the average illuminance of the passenger lounge on a clear day was 341.1 lux. The average illuminance of the passenger lounge on an overcast day was 338.4 lux (Table 6).

According to the work plane illuminance recommendation for large office spaces [16], occupants can be accepted for both paper and computer work with a lighting comfort of illuminance between 300-500 lux.

3.4 Cooling Load Comparison against the Energy Benchmarking for Cooling System

In order to assess energy performance in airports, energy consumption was compared between the recorded energy consumption in 2010 and average energy intensity benchmark. Energy intensity benchmark for airport is derived from extensive worldwide research into available and appropriate case studies. The energy intensity per floor area benchmark for large airport is 579.6 kWhm⁻² including Heating Ventilation and Air Conditioning (HVAC), lighting and equipment operation [35].

According to the total energy consumption data from the cooling water supplier agency, District Cooling System and Power Plant Ltd., in 2010, the total energy consumption was 1,132.50 kWhm⁻². It was very high compared against the benchmark due to the high solar altitude and ambient temperatures in the tropical climates. This clearly indicates that this
passenger lounge has the overheating problem causing the excessive use of the cooling system to keep the space thermally comfortable.

3.5 Subjective assessments results

The study only presents the section of the questionnaire survey pertaining to thermal comfort. This included air temperature, humidity, air movement and overall thermal comfort. A seven-point ASHRAE sensation scale was used to evaluate thermal sensation and impressions of comfort with regard to thermal comfort, visual comfort and indoor air quality [15].

Fig. 12(a) and 12(b) display the thermal sensation and impressions of comfort with temperature and humidity. Only 14.62% of respondents indicated ‘neutral’. The majority of temperature sensation responses were concentrated in the ‘slightly warm’ category at 41.62%. The humidity sensation responses were concentrated in the ‘slightly humid’ category at 29.77%.

Interestingly, 26.0% of respondents indicated ‘slightly cool’ which their dominant working period was the night shift occupants. It was observed that the day shift responses claimed that the air temperatures were ‘slightly warm’ while the night shift responses claimed that the air temperatures were ‘slightly cool’.

Fig. 13(a), 13(b) and 13(c) reveal that the majority distribution of subjective responses on ‘air movement’ was under the category of ‘slightly still’ (22.13%) and ‘air freshness’ was under the category of ‘neutral’ (33.68%), respectively. The responses from the total occupants on ‘air quality satisfactory’ were biased towards the ‘neutral’ category (26.01%).

Fig. 14(a) and 14(b) present the subjective responses to visual conditions. There was a slight bias towards ‘slightly dark’ at 25.85% and ‘neutral’ at 26.01%; while 28.46% of respondents indicated ‘neutral’. The majority of the visual comfort satisfaction vote was within the ‘neutral’ category at 27.15% and ‘slightly uncomfortable’ category at 26.37%.

3.6 Comparison of the simulation results with the measurement and subjective studies

Apart from considering indoor thermal comfort by Tas predicted operative temperatures and the questionnaire survey, the Tas models predicted values show fairly good agreement with this survey. The highest predicted operative temperature on the passenger lounge was around 29.1°C on both clear and overcast summer days. The highest operative temperature on the top floor was 33.2°C on a clear summer day and 31.8°C on an overcast summer day. From the above distribution of votes, the occupants perceived thermal discomfort in this passenger lounge of Suvarnabhumi Airport Terminal. In terms of the level of satisfaction in each season, the majority of respondents (54.05%) voted they were ‘dissatisfied’ in summer, 39.95% in winter and 46.21% in rainy weather. The thermal environment was also marginally unacceptable according to the respondents’ vote.

The measured indoor air temperature within the departure lounge floor over the twenty days remained stable and marginally swung between 21.8°C and 26.9°C, while those on the top floor swung between 24.6°C and 35.4°C. The indoor air temperatures within the departure lounge floor were within the adaptive thermal comfort standard [15] at 23-26°C. In contrast, the indoor air temperatures on the top floor were considerably exceeded the same standard, an event which occurred around midday for 4-5 hours almost every day. This temperature rise confirms the idea that the majority of respondents vote from subjective assessment were ‘uncomfortable’ in this passenger lounge especially on the top floor.

In addition, the predicted inner surface glazed temperatures could be risen to 52~59°C in summer and 36~45°C in winter which could penetrated deep to this departure lounge. Moreover, the heat up of the inner surface glazed resulted in high mean radiant temperatures (MRT) on the occupancy area to 29°C in summer and 28.4°C in winter which caused to the occupancy discomfort and the existing air-conditioning system to cope with this load.

For visual environment, the predicted average lighting levels were 350~370 lux in summer and 338~343 lux in winter. Even though this level appropriate for paper work and computer work according to the illuminance recommendation for work plane [16], but the predicted minimum lighting levels were also as low as 189~205 lux in summer and 170~180 lux in winter. Throughout the measurements, the natural light only benefits some areas underneath transparent roofs within the large glazed air-conditioned concourse space. The subjective assessments also found that visual comfort had negative ratings when considering the ‘visual condition’ regarding the amount of light for working. It was noted that the passenger lounge on the ground floor was lacking in natural light in some areas.
4. CONCLUSIONS

This paper was intended to obtain the airport officers and staff groups' qualitative feedback on their experience with the existing internal environment in a passenger lounge within a large glazed air-conditioned airport terminal building in Thailand by employing objective measurements and subjective assessments. Due to, limited resources and measurement period, field study would be incomplete and cannot provide accurate results. Computer modelling is thus an additional tool in the integrative approach for indoor environment quality assessment and analysis to improve its comfort and energy performance.

According to the field measurement and thermal simulation results taken, they revealed the main factor to contributed thermal condition in the glazed air-conditioned terminal is due to solar heat gain from solar radiation entering from the transparent component, especially the glazed roof. The high surface temperature that leads to high radiation heat to the space was considered to be the main cause for the negative effects on the thermal comfort resulting in more energy consumption from the air-conditioning system. There was a reasonable correlation between the results of measurement and prediction.

It was noticed that the airport has a higher energy consumption rate compared to the average international airport energy intensity benchmark. This reinforces the idea that the terminal building would experience the overheating problem causing the excessive use of the cooling system to keep a comfortable environment for occupants.

Based on sound analysis of the objective measurements, subjective assessment and computer modelling simulation results of the success of the space, the design of the large glazed air-condition terminal of this airport does not perform well in terms of the temperature and light levels experienced in its spaced by airport workers. It was found that there is also the high probability of encountering significant thermal and visual discomfort in the large glazed air-conditioned airport terminal, in this hot, humid climate of Bangkok, Thailand.

Apart from considering internal environment quality assessment by an integrative approach, it is believed that the performance assessments for such a complex building should be carried out at the initial design stage to avoid problems such as overheating etc. However, to resolve these problems, it was recommended that the large glazed terminal would be provided suitable sunshade that is costly to remedy once built.

Appendix

TERMAL and VISUAL ENVIRONMENTAL QUALITY ASSESSMENT of an AIRPORT TERMINAL in the TROPICS QUESTIONNAIRE

Researcher: Mr. Kittitach Pichatwatana

Supervised by: Dr. Fan Wang, Prof. Sue Roaf

Email: kp126@hw.ac.uk

Mobile: (44)7401380702

This survey is conducted as part of a doctoral research programme at the School of the Built Environment, Heriot - Watt University. It aims to assess the general environment performance of Suvarnabhumi Airport Terminal with respect to thermal comfort, lighting, ventilation for a member of staffs. This research has been approved by the relevant Ethics Committee. Be assured that your responses will be completely anonymous and will only be used for the above purpose.

A. GENERAL QUESTIONS

1. Gender
   - Male
   - Female

2. Age
   - < 30 yr
   - 31-40 yr
   - 41-50 yr
   - >51 yr

3. Status
   - AOT Employee
   - Thai Airline employee
   - Other International Airline employee
   - Other Domestic Airline Employee
   - Shop Attendant
   - Other …………. (Identify)

4. Nationality
   - Thai
   - Other……………………….. (Identify)

5. How long do you spend in the airport in each day?
6. What kinds of typical cloth do you wear?
- Typical business suit
- Light working ensemble
- T-shirt with trousers/blouse

7. Where do you work?
- Check in
- Baggage attendant
- Customer Service
- Other ............ (Identify)

<table>
<thead>
<tr>
<th>B</th>
<th>LEVEL of SATISFACTION and OVERALL PERCEPTION in THE AIRPORT</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Level of satisfied during Summer (March-May)</td>
</tr>
<tr>
<td></td>
<td>1 Strongly Satisfied 2 Satisfied 3 Dissatisfied 4 Strongly Dissatisfied</td>
</tr>
<tr>
<td>9</td>
<td>Level of satisfied during Winter (November-February)</td>
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<tr>
<td></td>
<td>1 Strongly Satisfied 2 Satisfied 3 Dissatisfied 4 Strongly Dissatisfied</td>
</tr>
<tr>
<td>10</td>
<td>Level of satisfied during Rainy (June-October)</td>
</tr>
<tr>
<td></td>
<td>1 Strongly Satisfied 2 Satisfied 3 Dissatisfied 4 Strongly Dissatisfied</td>
</tr>
<tr>
<td>11</td>
<td>Overall perception of the indoor thermal quality</td>
</tr>
<tr>
<td></td>
<td>1 Clearly Acceptability 2 Acceptability 3 Unacceptability 4 Clearly Unacceptability</td>
</tr>
</tbody>
</table>

<table>
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<th>THERMAL SENSATION and IMPRESSION of COMFORT with regard to THERMAL COMFORT.</th>
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<td>Overall temperature comfort</td>
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<td></td>
<td>-3 Cold -2 -1 0 Neutral 1 2 3 Hot</td>
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<tr>
<td>13</td>
<td>Humidity</td>
</tr>
<tr>
<td></td>
<td>-3 Much too dry -2 -1 0 Neutral 1 2 3 Much too humid</td>
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<table>
<thead>
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<th>IMPRESSION of COMFORT with regard to AIR QUALITY.</th>
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<td>Each question, select the level that best describes your primary workstation.</td>
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</tr>
<tr>
<td></td>
</tr>
<tr>
<td>15</td>
</tr>
<tr>
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<td>16</td>
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<tr>
<td></td>
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</tbody>
</table>

<table>
<thead>
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</thead>
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</tr>
<tr>
<td></td>
</tr>
<tr>
<td>18</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

19. Is there other aspect of the airport environment you would like to comment on?
..................................................................................................................................................................................
END OF THE QUESTIONNAIRE THANK YOU FOR YOUR TIME

References


[33] Anunnathapong, M., 2013 Design and Assessment of Atrium Indoor Shading for Tropic Building, MSc Dissertation, School of Built Environment, Heriot-Watt University.


a) Viewing the departure lounge from the 6th floor viewpoint

b) Departure lounge floor plan

c) Terminal Building Section

Fig. 1 Departure lounge of Suvarnabhumi Airport Terminal
Fig. 2 Climate data for 30 year average (1961-1990) - Bangkok Metropolis (http://www.tmd.go.th)
a) Section A of the airport terminal building with location of thermal sensors

b) Plan of the airport terminal building with location of thermal sensors

**Fig. 3** Positions of the sensors in the airport passenger lounge

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a) The Passenger Lounge Floor Plan

b) Computer Model

**Fig. 4** Suvarnabhumi International Airport Terminal configuration model
Fig. 5 Measured air & transparent roof temperatures compared with solar irradiation and RH
Fig. 6: Measured illuminance on the passenger lounge floor at 13.00-14.00 on 28th Sep 2012.

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<tr>
<th>Time</th>
<th>0-99 lux</th>
<th>100-299 lux</th>
<th>300-500 lux</th>
<th>Over 500 lux</th>
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<tr>
<td>12:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14:00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

°C

- **External Temp (°C)**
- **Measured Temp (°C)**
- **TAS Predicted Temp (°C)**
a) On the clear day, 12\textsuperscript{th} of September

![Graph showing temperature comparison]

b) On the cloudy day, 28\textsuperscript{th} of September

**Fig. 7** Comparison between the measurement and model prediction

![Bar chart showing illuminance comparison]

**Fig. 8** Comparison of average illuminance between measurement and simulation
a) Summer clear day: 1st May 2012

b) Summer cloudy day: 3rd May 2012

c) Winter clear day: 26th December 2012
d) Winter cloudy day: 7th December 2012

**Fig. 9** Comparison of the glazed surface temperature in the passenger lounge

- **Surface temperature (°C)**
  - Outdoor
  - Glazed roof

- **MRT (°C)**
  - Outdoor
  - Base Model grd Floor
  - Base Model 6th ceiling

---

**Notes:**

- **a)** Summer clear day: 1st May 2012
- **b)** Summer cloudy day: 3rd May 2012
Fig. 10 Comparison of the MRT of the ground floor and the top floor ceiling

a) Summer cloudy day: 3rd May 2012

b) Winter clear day: 26th December 2012

c) Winter cloudy day: 7th December 2012
b) Summer cloudy day: 3rd May 2012

c) Winter clear day: 26th December 2012

d) Winter cloudy day: 7th December 2012

Fig. 11 Comparison of the air temperatures of the seventh floor ceiling and under glazed roof
a) Summer clear day: 1\textsuperscript{st} May 2012

b) Summer cloudy day: 3\textsuperscript{rd} May 2012

c) Winter clear day: 26\textsuperscript{th} December 2012
d) Winter cloudy day: 7\textsuperscript{th} December 2012

Fig. 12 Comparison of the operative temperature of the passenger lounge and top floor view point

Fig. 13 Thermal Sensations and Impress of Comfort
a) Air Movement

b) Air Freshness
c) Air Quality Satisfactory  
Fig. 14 Indoor air qualities

a) Visual condition

b) Visual comfort satisfaction  
Fig. 15 Visual comforts and visual perception
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<thead>
<tr>
<th>Year</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2010</th>
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<tbody>
<tr>
<td>Jan</td>
<td></td>
<td>2.18x10^7</td>
<td>2.34x10^7</td>
<td>1.97x10^7</td>
<td>2.38x10^7</td>
<td>2.64x10^7</td>
</tr>
<tr>
<td>Feb</td>
<td></td>
<td>2.28x10^7</td>
<td>2.30x10^7</td>
<td>2.31x10^7</td>
<td>2.41x10^7</td>
<td>2.47x10^7</td>
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<tr>
<td>Mar</td>
<td>8.53x10^6</td>
<td>2.96x10^7</td>
<td>2.74x10^7</td>
<td>2.78x10^7</td>
<td>2.74x10^7</td>
<td>2.77x10^7</td>
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<tr>
<td>Apr</td>
<td>5.83x10^6</td>
<td>2.85x10^7</td>
<td>2.84x10^7</td>
<td>2.78x10^7</td>
<td>2.84x10^7</td>
<td>2.73x10^7</td>
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<td>May</td>
<td>6.13x10^6</td>
<td>2.85x10^7</td>
<td>2.83x10^7</td>
<td>2.73x10^7</td>
<td>2.90x10^7</td>
<td>2.80x10^7</td>
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<tr>
<td>Jun</td>
<td>7.03x10^6</td>
<td>2.86x10^7</td>
<td>2.73x10^7</td>
<td>2.71x10^7</td>
<td>2.67x10^7</td>
<td>2.73x10^7</td>
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<td>Jul</td>
<td>1.66x10^7</td>
<td>2.82x10^7</td>
<td>2.73x10^7</td>
<td>2.65x10^7</td>
<td>2.74x10^7</td>
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<td>1.71x10^7</td>
<td>2.81x10^7</td>
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<td>2.66x10^7</td>
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<td>2.01x10^7</td>
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<td>2.50x10^7</td>
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<td>2.50x10^7</td>
<td>2.56x10^7</td>
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<td>Nov</td>
<td>2.64x10^7</td>
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<td>2.32x10^7</td>
<td>2.27x10^7</td>
<td>2.69x10^7</td>
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<td>Dec</td>
<td>2.27x10^7</td>
<td>2.41x10^7</td>
<td>1.92x10^7</td>
<td>2.29x10^7</td>
<td>2.39x10^7</td>
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<td>Total (KWh)</td>
<td>1.58x10^8</td>
<td>3.14x10^8</td>
<td>3.05x10^8</td>
<td>3.02x10^8</td>
<td>3.11x10^8</td>
<td>3.27x10^8</td>
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<td>Total/ floor area (KWhm^-2)</td>
<td>281.10</td>
<td>556.99</td>
<td>541.37</td>
<td>536.17</td>
<td>551.78</td>
<td>580.82</td>
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Table 1 Amounts of chilled water to cooling coil and electricity consumption of Suvarnabhumi Airport (kWh) [18]

<table>
<thead>
<tr>
<th>Indoor condition departure lounge zone (floor area=40,500 m²)</th>
<th>Indoor condition void zone (floor area=40,500 m²)</th>
<th>Indoor condition office zone (floor area=20,184 m²)</th>
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<tbody>
<tr>
<td>Infiltration rate (24 hours)</td>
<td>0.5 ach</td>
<td>Infiltration rate (24 hours)</td>
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<td>lighting gain</td>
<td>12 Wm⁻²</td>
<td>lighting gain</td>
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<tr>
<td>Occupancy sensible gain (6050+2206x75W)/40,500 m²</td>
<td>15.3 Wm⁻²</td>
<td>Occupancy sensible gain (883x75W)/20,184</td>
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<tr>
<td>Occupancy latent gain (6050+2206x55W)/40,500 m²</td>
<td>11.2 Wm⁻²</td>
<td>Occupancy latent gain (883x55W)/20,184</td>
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<td>Equipment Sensible gain (400×195×0.5)/40,500 m²</td>
<td>5.0 Wm⁻²</td>
<td>Equipment Sensible gain (883×195×0.5)/20,184</td>
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Table 2 Suvarnabhumi Airport Terminal Indoor Conditions
### Table 3 Properties of some key building elements used in the airport terminal model

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<th>Specification</th>
<th>Material</th>
<th>Width (mm)</th>
<th>Solar Absorptances</th>
<th>Solar Reflectance</th>
<th>Conductivity (W/m.K)</th>
<th>Specific Heat (J/kg°C)</th>
<th>Density (Kg/m³)</th>
<th>Vapour Diffusion Factor [g/(m.h.pal)]</th>
<th>Transmittance</th>
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<tr>
<td>Floor</td>
<td>Terrazzo tiles</td>
<td>350</td>
<td>0.65</td>
<td>0.35</td>
<td>1.75</td>
<td>850</td>
<td>2400</td>
<td>48</td>
<td>-</td>
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<tr>
<td></td>
<td>Concrete screed</td>
<td>50</td>
<td>0.65</td>
<td>0.35</td>
<td>1.28</td>
<td>1000</td>
<td>2100</td>
<td>34</td>
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<tr>
<td></td>
<td>Concrete 3%</td>
<td>200</td>
<td>0.65</td>
<td>0.35</td>
<td>0.87</td>
<td>920</td>
<td>1800</td>
<td>14</td>
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<td>Ceiling</td>
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<td>0.50</td>
<td>0.058</td>
<td>586</td>
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<td>Laminate Glass</td>
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<td>0.53</td>
<td>0.47</td>
<td>43</td>
<td>500</td>
<td>7800</td>
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<td></td>
<td>Mineral wool</td>
<td>90</td>
<td>0.53</td>
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<td>2700</td>
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<td>500</td>
<td>7800</td>
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#### Table 4 Performance Indicators and Their Interpretation [13]

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<th>Performance Indicator</th>
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<td>WORK PLANE ILLUMINANCE</td>
<td></td>
</tr>
<tr>
<td>&lt;100 lx</td>
<td>Too dark for paper and computer work</td>
</tr>
<tr>
<td>100-300 lx</td>
<td>Too dark for paper work/ acceptable for computer work</td>
</tr>
<tr>
<td>300-500 lx</td>
<td>Acceptable for paper work/ acceptable for computer work</td>
</tr>
<tr>
<td>&gt;500 lx</td>
<td>Ideal for paper work/ too bright for computer work</td>
</tr>
<tr>
<td>Date</td>
<td>Average External Temp. (°C)</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>12th Sep 2012</td>
<td>29.89</td>
</tr>
<tr>
<td>13th Sep 2012</td>
<td>28.99</td>
</tr>
<tr>
<td>14th Sep 2012</td>
<td>27.51</td>
</tr>
<tr>
<td>15th Sep 2012</td>
<td>27.60</td>
</tr>
<tr>
<td>16th Sep 2012</td>
<td>27.21</td>
</tr>
<tr>
<td>17th Sep 2012</td>
<td>27.08</td>
</tr>
<tr>
<td>18th Sep 2012</td>
<td>27.26</td>
</tr>
<tr>
<td>19th Sep 2012</td>
<td>27.61</td>
</tr>
<tr>
<td>20th Sep 2012</td>
<td>28.01</td>
</tr>
<tr>
<td>21st Sep 2012</td>
<td>27.55</td>
</tr>
<tr>
<td>22nd Sep 2012</td>
<td>28.36</td>
</tr>
<tr>
<td>23rd Sep 2012</td>
<td>28.83</td>
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<tr>
<td>24th Sep 2012</td>
<td>28.90</td>
</tr>
<tr>
<td>25th Sep 2012</td>
<td>27.92</td>
</tr>
<tr>
<td>26th Sep 2012</td>
<td>29.28</td>
</tr>
<tr>
<td>27th Sep 2012</td>
<td>27.38</td>
</tr>
<tr>
<td>28th Sep 2012</td>
<td>26.35</td>
</tr>
<tr>
<td>29th Sep 2012</td>
<td>27.70</td>
</tr>
<tr>
<td>30th Sep 2012</td>
<td>28.28</td>
</tr>
<tr>
<td>1st Oct 2012</td>
<td>28.51</td>
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</tbody>
</table>

**Table 5** Average daily transparent roof surface temperatures comparison

<table>
<thead>
<tr>
<th>lux</th>
<th>Hot clear day</th>
<th>Hot overcast day</th>
<th>Cold clear day</th>
<th>Cold overcast day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average illuminance</td>
<td>373.72</td>
<td>351.09</td>
<td>341.08</td>
<td>338.43</td>
</tr>
<tr>
<td>Maximum illuminance</td>
<td>613</td>
<td>569</td>
<td>567</td>
<td>552</td>
</tr>
<tr>
<td>Minimum illuminance</td>
<td>205</td>
<td>189</td>
<td>171</td>
<td>180</td>
</tr>
</tbody>
</table>

**Table 6** Predicted illuminance within the passenger lounge