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Article

A Field Study on Thermal Comfort and Cooling Load Demand Optimization in a Tropical Climate

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Abstract: Energy consumption to cool an indoor environment is a substantial part of total energy end-use, particularly in a tropical climate with high energy demand for cooling. To improve energy efficiency, cooling systems can be optimized using a variety of neutral indoor temperatures to maintain a balance between an occupant's thermal comfort and cooling energy demand. This explanatory study investigated the thermal quality and cooling energy demand of a Platinum-certified office building in the tropical climate of Malaysia. The investigation aimed to suggest a balance between occupant thermal comfort and cooling energy demand. The thermal investigation includes an objective field measurement that implements environmental equipment to monitor thermal quality and a subjective occupant's thermal feedback using a questionnaire survey. To calculate cooling energy demand, the total equivalent temperature difference method (TETD) is applied. The results suggested an occupant's cooling sensation of around 24 °C, with no significant difference concerning age and gender. Cooling load calculation indicated a 36% energy reduction by increasing air temperature to 26 °C, for occupants to feel thermally comfortable in a tropical climate. These findings contribute to improving sustainable energy policies, sustainable construction, and thermal comfort improvement for a tropical climate.

Keywords: thermal quality; cooling energy demand; energy-efficient design; tropical climate; green building index

1. Introduction

Cooling the indoor environment is essential in tropical climates to provide thermal comfort. Within this climate, heating, ventilation, and air-conditioning (HVAC) systems are the main sources to provide indoor thermal comfort with excessive energy consumption [1]. Conversely, the power reduction in tropical climates is necessary for buildings to reduce electricity cost [2]. This can bring complications between providing thermal comfort and energy efficiency [3], particularly for green buildings aiming to reduce cooling energy demand. Thermal comfort has a direct impact on energy consumption of any building, as any occupant discomfort leads to a modification of controls to non-optimal levels [4,5]. To overcome this challenge, natural ventilation is proposed as an alternative solution [6,7]. However, the use of an HVAC system is still dominant in a hot-humid climate.

Among the building services, especially in tropical countries, there is a significant growth in applying HVAC systems to cool indoor environments. Statistical data shows that cooling systems cover 50% of building energy use and 20% of total energy consumption in the United States of America [8]. Overworking of the HVAC system in buildings can be considered as a flaw in mechanical system design, proven by thermal dissatisfaction as well as excessive energy consumption.

Hoyt and Lee [9] indicated that, by increasing cooling setpoints by 1 °C, energy consumption decreases significantly up to 15% annually. Particularly for Malaysia, Kwong and Adam [2] concluded that an annual reduction of 2150 GWh energy consumption can be achieved by increasing 2 °C in the thermostat setpoint. According to PTM [10], the buildings energy index (BEI) for Malaysian office buildings stays within the range of 100 to 450 kWh/m²/year. The average BEI of 250 kWh/m²/year is also reported by the same source for Malaysian office buildings. However, only about 30% of office buildings in Malaysia can achieve the target of less than 220 kWh/m²/year. This threshold is considered as a benchmark by Malaysian standard MS 1525 [11]. Thus, thermal comfort evaluation to determine the occupant's thermal perception and neutral temperature is a proper strategy to reduce power consumption [12].

Basically, the design and evaluation of indoor thermal comfort relies on universal standards such as ISO 7730 [13], EN 16798 [14], ASHRAE Standard 55 [15] and/or in Malaysia, MS 1525 [11]. Particularly, MS 1525 [11] was developed to address occupant comfort and minimum energy efficiency criteria for non-residential buildings. These standards mostly depend on Fanger's model to predict and define the acceptable indoor thermal environment. Fanger's PMV-PPD model was developed to illustrate thermal sensation in seven-point scales, resulting from numerous experiments on human subjects in several environments [16]. Fanger's model provides a set of equations to compute predicted mean vote (PMV) and predicted percentage dissatisfied (PPD). With this, percentages of thermally satisfied occupants can be predicted by employing the metrics PMV and PPD [8].

The PMV-PPD model is extensively applied in buildings with HVAC systems in cold and warm climates during both summer and winter. However, Nicol [17] believes that universal standards [15,18] based on Fanger's PMV-PPD, do not appropriately deliver a thermally comfortable indoor environment in a tropical climate. Besides the PMV-PPD model, adaptive thermal comfort is also studied based on the climate [19–21]. These investigations are due to thermal adaptation of individuals, which is correlated with factors such as geographic location and climate, time of year, gender, race, and age [22]. For instance, Maykot and Rupp [23] indicated that the neutral temperature for females is higher than for males. Concerning the climate, Lovins [24] implied that the perception of comfort varies between different climates and is influenced by localised culture.

Regarding tropical climates, studies were conducted in countries such as Malaysia to determine acceptable indoor thermal comfort. For instance, the acceptable indoor temperature is found to range between 21–26 °C for a variety of buildings in this climate [25–29]. In addition, Kwong and Adam [2] reviewed the literature on the thermal comfort of office buildings in tropical climates. The findings suggest a range of neutral temperatures between 24.2 and 28.3 °C. Thermal dissatisfaction is one of the most common complaint sources of the indoor environment quality (IEQ) of office buildings in different climates [30,31].

To achieve an acceptable thermal quality for office buildings in a tropical country such as Malaysia, a significant portion of total electricity end usage is related to the HVAC system. Thus, determining neutral temperature is essential for different air-conditioned buildings to improve thermal comfort and to reduce excessive cooling load resulting from overworked air-conditioning systems. The cooling load is the amount of heat rate that should be removed to keep indoor temperature at a comfortable level [13].

Generally, heat gain through building envelopes, such as walls, roofs, and windows, is attributed to a major portion of the cooling load [32]. Cooling load calculation is a complicated process due to the thermal mass effect of building envelopes and the fluctuations of outdoor conditions. Although there are various methods to investigate and calculate the cooling load of buildings, the total equivalent temperature difference (TETD) is a widely accepted method to determine heat gain through the structures. TETD is a proposed method by ASHRAE to calculate cooling load according to heat gain in a transient condition. To calculate the cooling load in a transient condition, the dynamic thermal properties of building envelopes should be evaluated. The TETD method calculations depend on time lag and decrement factor to accurately predict cooling load [33]. Time lag (φ) and decrement factor (f) are important dynamic parameters to evaluate the heat storage capacity of a wall system. A heatwave has a specific amplitude and a specific wavelength. The wall system, as a thermal mass, reduces the amplitude of the heatwave. The time lag represents the time variance between the heatwave peak occurring outdoors and indoors. In addition, the decrement factor describes the amplitude ratio of the heatwave before and after passing through the wall. Literature review shows that assessing the time lag and decrement factor are considered among the most useful methods to determine the HVAC load [34–36].

Concerning the substantial impact of cooling load on thermal comfort in a fully air-conditioned building, optimizing thermal comfort and cooling load demand can be challenging for green buildings in a tropical climate. Particularly in Malaysia, green building index (GBI) platinum-certified office buildings should achieve maximum energy performance of 90 kWh/m²/year but also provide thermal satisfaction for at least 80% of occupants [37]. The GBI is an environmental rating system tool in Malaysia, similar to the Leadership in Energy and Environmental Design (LEED) in the United State of America. Regard energy efficiency, Kwong and Adam [2] reviewed thermal comfort and energy efficiency in tropical climates, including in Malaysia, and indicated the importance of thermal investigation to optimize indoor air temperature and energy efficiency by using computational simulation tools. To address this challenge, in this field study, thermal investigation was integrated with predicting cooling energy demand using TETD for a GBI platinum-certified office building in the tropical climate of Malaysia. Thus, a comprehensive field study, including subjective investigation of thermal sensation vote (TSV) and objective measurement of thermal variables in the indoor built environment, is necessary. Besides optimizing thermal comfort based on energy efficiency, it is crucial to evaluate the amount of energy consumption regarding different setpoint temperatures to predict cooling load demand. As illustrated in Figure 1, this study aims to determine the optimum set-point of indoor air temperature for a GBI office building in Malaysia through the following steps:

1. Investigating the thermal quality of a GBI Platinum-certified office building in Malaysia through both objective and subjective measurements;
2. Comparing PMV (Fanger's PMV-PPD model) with TSV;
3. Calculating the amount of cooling energy demand with the TETD method for various neutral indoor set-point temperatures;
4. Determining the optimum indoor air temperature based on occupant comfort and cooling energy demand.

To achieve the objectives of this study, the paper is structured as follows: an introduction is given in Section 1; applied methodology explaining subjective and objective measurement and TETD method construction to calculate cooling energy demand is explained in Section 2, followed by results and discussion of findings in Section 3. Lastly, Section 4 summarizes and concludes this paper.
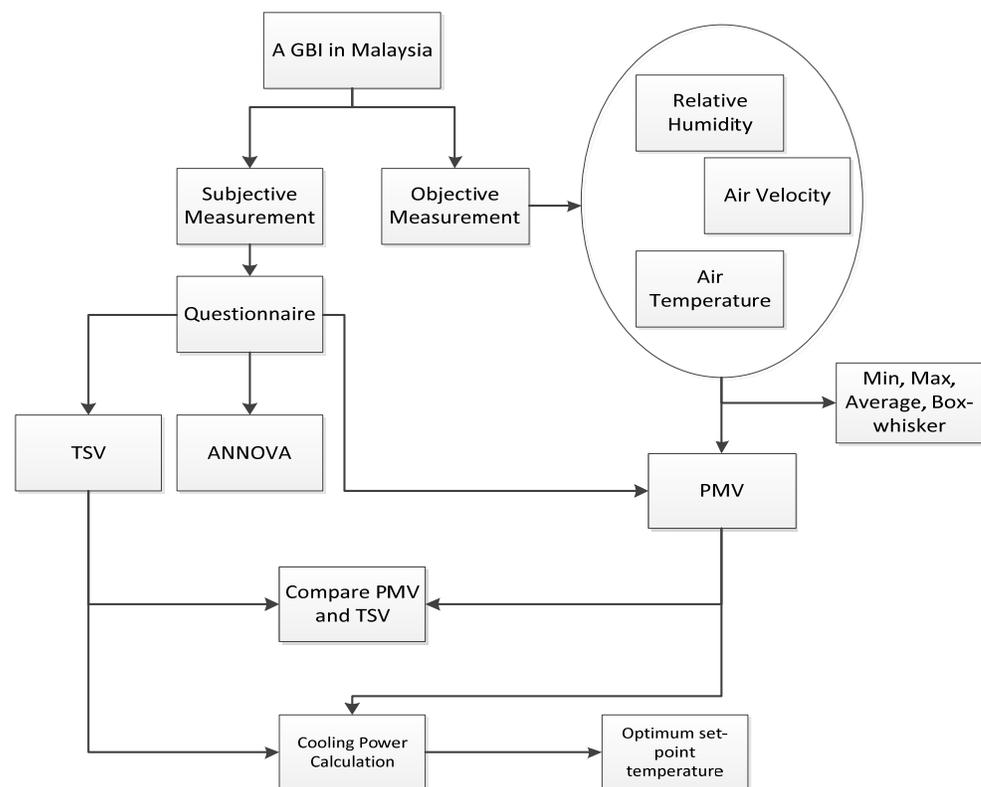
Figure 1. Analytical framework of thermal optimization.

Green Building Index

GBI was developed in 2009 by the Malaysian Institute of Architect and the Association of Consulting Engineers Malaysia (ACEM) [37]. GBI awards buildings based on six assessment criteria, which are: Energy Efficiency, Indoor Environment Quality, Sustainable Site Planning and Management, Material and Resources, Water Efficiency and Innovation [37]. Based on the total points gained from assessment criteria, buildings are awarded and classified into four categories as Platinum, Gold, Silver, Certified respectively, in which Platinum is the highest classification [37].

2. Materials and Methods

A case study approach was adopted to achieve a comprehensive interpretation of thermal quality in a Platinum-certified office building. This kind of research emphasizes the few events or conditions and their interactions to provide a thorough interpretation of the events [38]. This study included an investigation of thermal sensation vote (TSV), thermal quality effect on occupant's satisfaction, occupant's characteristic effect on thermal satisfaction for gender, age, location, and type of office, and thermal quality effect on perceived productivity. In addition, based on the investigation, the cooling load demand was optimized according to different neutral indoor temperatures using heat transfer equations in a transient condition.

The case study was selected based on several criteria: being an office building, Platinum GBI certificate, located in Kuala Lumpur, and in an operational phase for a minimum of two (2) years. Figures 2 and 3 illustrate the site plan and plan layout of the selected office building, respectively.
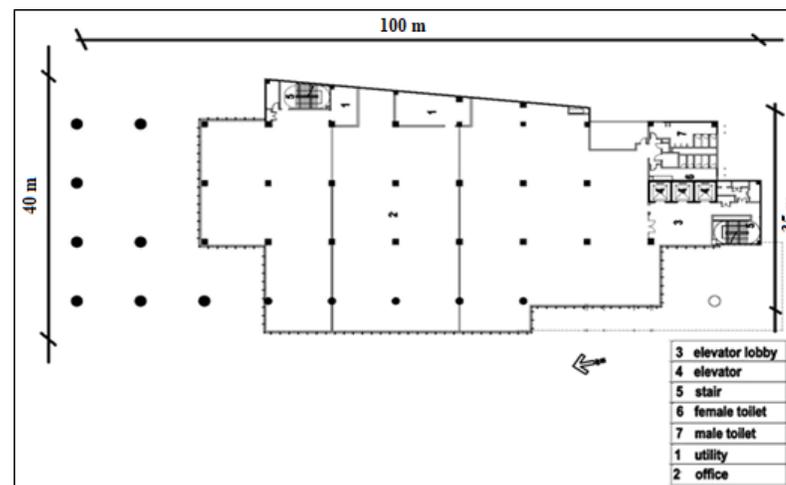
Figure 2. Location of the case study building.

Figure 3. Plan layout of the selected office building—open plan office.

2.1. Office Building Characteristics

The selected building is in Kuala Lumpur, Malaysia. The office building is Platinum-certified by GBI under the Noun-Residential New Construction (NRNC) category. Key data of the building is explained in Table 1. The underfloor air distribution (UFAD) system provides cooling and ventilation. UFAD is a system for providing ventilation by raising the floor and applying an air plenum below it to distribute the conditioned air through vents or diffusers where the vents can be controlled to adjust the air outlet [39]. Generally, there are limited opportunities for occupants to adjust the thermal condition using an environmental control system. The ability to control the floor vents does not have a huge impact on indoor thermal condition. In addition, there are no operable windows to adjust the thermal and air quality with natural ventilation.

Table 1. Key data of the case study building.

Characteristics	Details
Occupant possession	2014
No. story	9
Gross floor area	33,798 m²
Net floor area	14,087 m²
Structure	Steel reinforced concrete (SRC)
Façade finishing	Double glass curtain wall
Access to public transport	Bus
Air conditioning system	Underfloor Air Distribution (UAFD)
Underfloor vents	Yes
Floor/roof radiant cooling	No
Adjustable vents	Yes
Operable windows	No
Lighting type	Fluorescent, Personal LED
Window blind, roller shade, fixed shading system	Yes
Window to wall ratio (WWR)	About 55%
Exterior shades	No
Interior separators	Medium-density fibreboard (MDF), and Glass
Atrium	No
Courtyard	Yes
Occupants' capacity	250
Employees/occupants	60–100
Year of GBI certificate	2014

2.2. Thermal Quality Monitoring

Indoor thermal quality was investigated with full-scale (objective) measurement and occupant survey (subjective measurement).

2.2.1. Full-Scale Measurement

To perform the full-scale measurement, the subjective floors including open offices were monitored from 21 May to 10 August 2019. During this period, the indoor thermal temperature was monitored using six sets of environmental loggers adjusted to 5 min interval sampling. However, data extracted from loggers were limited to the building's operational hours from 8:00 a.m. to 6:00 p.m. Average values of the thermal variables were calculated using loggers' outputs. For instance, data logged at 1:00 p.m. from all sensors were accumulated and divided by six to produce an average value for 1:00 p.m. This way, a daily average from 8:00 a.m. to 6:00 p.m. for each variable was created. Then, the average value for the variable was calculated according to the daily average spectrum.

Thermal parameters such as air temperature (T_a), relative humidity (RH) and air velocity were measured with calibrated instruments (Figure 4c). In addition, regarding mean radiant temperature, the difference between indoor air temperature and mean radiant temperature was negligible under moderate outdoor conditions. Thus, the mean radiant temperature can be assumed equal to the indoor air temperature [40–42]. As illustrated in Figure 4a, b, instruments were installed on a pole close to the occupants' workstations at a height of approximately 1.1 m above the finished floor, following ISO 16000-1 [43]. To avoid the radiative temperature effect on devices, 0.8 m horizontal distance with other surfaces was applied to the devices' location. Table 2 summarises loggers' specifications.
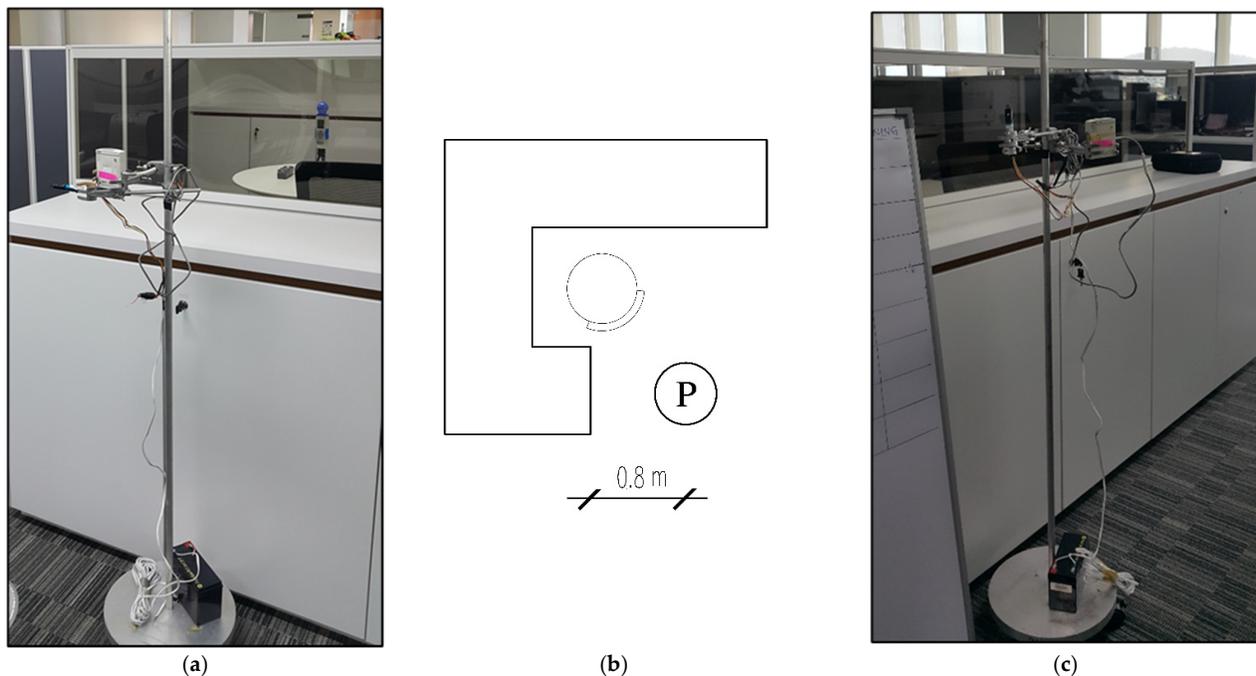
Figure 4. Examples of installed instruments. (**a**) Portable pole with loggers; (**b**) sample of pole location close to the work-station; (**c**) air temperature, air velocity, RH measurement.

Table 2. Specification of instruments.

IEQ Variable	Environmental Logger	Range and Accuracy
Air temperature	HOBO-U12-012 [a] (Manufactured by Onest, data logger)	between −20 to 70 °C, accuracy ±0.35 °C from 0 to 50 °C
Relative humidity		between 5% and 95% RH with an accuracy of ±2.5%
Air velocity	T-DCI-F900-S-O [a] (Connected to HOBO-U12-012 as an external sensor, manufactured by Onest)	Accuracy greater than 10% of the reading or ±0.05 m/s or 1% full scale

[a] Loggers were calibrated and tested for accuracy.

2.2.2. Occupant's Survey

A paper-based questionnaire survey was conducted within the full-scale measurement by 2 July. The occupants were informed about the survey 24 h earlier. In addition, participating in the survey was optional. On the survey day, the questionnaires were distributed to occupants by the start of working hours and collected from their tables after working hours. Many believe this method is the most effective and best systematic technique of investigation to explore and examine mutual interactions between the building and occupants' needs [44–46]. Items in the questionnaire were measured using seven scale points following ASHRAE Standard 55 [15]. The summary of information collected with the questionnaire is presented Table 3.

Table 3. Information collected by questionnaire survey.

Category	Question
Background information	Age, Sex, Years of working in the building, Type of the working office, Sitting near a window
Thermal comfort	Overall Thermal comfort Temperature cold-hot Temperature stable-various Air dry-humid

Fifty-three valid respondents were collected from 81 distributed questionnaires. The uncompleted questionnaires were considered invalid. According to Cochran [47], the sample size and response rate came with a 95% confidence level and 8% error of the building population. Females accounted for 47% and males at 53% of the responses. In addition, 51% and 49% reported ages of 30 years or above and under 30 years, respectively. Only 34% reported sitting near windows. Further information on the distribution of the respondents, including a reply to work experience in the building and type of the work office, is summarized in Table 4.

Table 4. Background and demographic of valid respondents.

		Case Study Building	
		N	**%**
Sex	Female	25	47
	Male	28	53
Age	Under 30	26	49
	30 and above	27	51
Work experience in building	Less than a year	20	38
	A year or more	33	62
Type of the work office	Normally occupied by 1	8	15
	Shared with 1 other	0	0
	Shared with 2–4 others	22	41
	Shared with 5–8 others	15	29
	Shared with more than 8 others	8	15
Do you sit next to a window?	Yes	18	34
	No	35	66

2.3. Fanger's PMV-PPD

Fanger's PMV-PPD model was developed to illustrate thermal sensations in seven-point scales resulting from numerous experiments on human subjects in several environments [16]. Fingers' model provides a set of equations to compute predicted mean vote (PMV) and predicted percentage dissatisfied (PPD).

Fanger's PMV-PPD model was employed in this study to: (1) compare PMV with TSV in a tropical climate and (2) suggest neutral temperatures as an input for energy usage calculation. To compute PMV and PPD, air temperature T_a (°C), relative humidity R_h (%), and air velocity V_a (ms^{-1}) are measured directly. Occupants' clothing value (Clo) was observed to be typical working indoor appearances, such as pants and shirts. Per the usual office workload, working on a desk with a computer was observed for metabolic rate (met).

2.4. Cooling Power Calculation

Cooling power calculation was applied to this study to: (1) predict energy usage for different neutral air temperatures and (2) correlate energy usage with thermal satisfaction for a tropical condition. The cooling power was calculated for the baseline model and the other models with different indoor air temperatures. For this study, all boundaries were considered solid except for air temperature.

The amount of energy consumption for cooling was directly affected by outdoor temperature [48]. The geographic location of Kuala Lumpur is at latitude 3.13° N and longitude 101.68° E. Kuala Lumpur's tropical climate is hot and humid. A ten-year period shows that outdoor temperatures of Kuala Lumpur from May to August are relatively uniform, with typical temperatures between 25.9 and 27.3 °C (Figure 5).
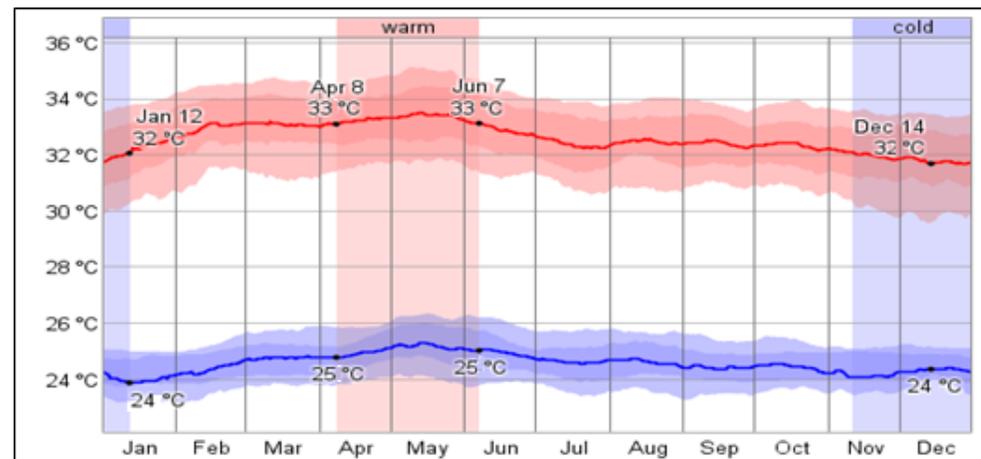

Figure 5. Daily average low and high temperatures with percentile bands Adapted with permission from ref. [49], 2021, ELSEVIER LICENSE.

Microclimate data were collected from Meteonorm 7 software, which is a comprehensive climatological database [50]. The collected data were used to investigate the effect of outdoor conditions on the indoor environment with Spearman's rho correlation test. The result of the test showed a positively strong significant correlation between indoor and outdoor air temperature fluctuation ($r = 0.905$; $p < 0.05$) as shown Table 5. Thus, outdoor air temperature is a significant predictor of indoor air temperature ($R^2 = 0.967$; $p < 0.05$). The total equivalent temperature difference method (TETD) was applied to calculate the cooling load. The total heat transfer coefficient, time lag, and decrement factors should be considered for cooling load calculation based on TETD. The governing equations are explained in the following sections.

Table 5. Correlation coefficient between indoor and outdoor temperatures.

Indoor Air Temperature	Outdoor Air Temperature
Correlation Coefficient	0.905 **
p value	0.000
R^2	0.967

** Correlation is significant at the level of $p < 0.01$ level (two-tailed).

2.4.1. Governing Equations for Cooling Load (Q)

The internal cooling load was not constant and changed during the day due to changing the outdoor condition and thermal mass phenomena of building envelopes [51]. The

TETD is a useful method to calculate the amount of external cooling load [52]. The following equation was applied to determine the amount of required cooling power caused by heat transfer through conduction:

$$Q = U. A. (TETD) \tag{1}$$

and TETD is:

$$TETD = T_{sa} - T_i + f(T_{sa,\emptyset} - T_{sa}) \tag{2}$$

where U is thermal transmittance (W/m², °C), A is the heat transfer area (m²), T_{sa} is the daily average sol-air temperature (°C), T_i is the design indoor air temperature (°C), f is decrement factor, and $T_{sa,\varphi}$ is the sol-air temperature for time lag hours ago (°C). The sol-air temperature is an outdoor variable, which is needed to calculate cooling load. This variable is based on both radiation and convection to predict the heat gain through exterior surfaces, and it is calculated using Equation (3):

$$T_{sa}(t) = \frac{T_{max} - T_{min}}{2} Cos\left(\frac{2\pi t}{P}\right) + \frac{T_{max} + T_{min}}{2} \tag{3}$$

2.4.2. Governing Equations for Total Heat Transfer Coefficient (U-Value), Time Lag (φ), and Decrement Factor (f)

These parameters are dependent on thermo-physical properties of the building envelope. In addition, the total heat transfer coefficient (U-value) of an envelope is directly related to its thermal resistance, which is calculated through the following equation:

$$U = \frac{1}{R_t} \tag{4}$$

The sol-air temperature for time lag hours ago ($T_{sa,\varphi}$) is calculated using the following equation:

$$T_{sa,\emptyset}(t) = T_{av} + |T|Cos(\omega t + \varphi) \tag{5}$$

Conversely, based on EN ISO 13786 [53], the heat transfer matrix can be defined as:

$$Z = \begin{pmatrix} T_2 \\ q_2 \end{pmatrix} = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \begin{pmatrix} T_1 \\ q_1 \end{pmatrix} \tag{6}$$

where T_1 and T_2 are temperatures in situations one and two, respectively. q_1 and q_2 are heat flux in situation one and two, respectively. In addition, the matrix elements can be calculated as follow:

$$Z_{11} = Z_{22} = \cosh(\propto)\cos(\propto) + j\sinh(\propto)\sin(\propto) \tag{7}$$

$$Z_{12} = -\frac{\delta}{2k}\{\sinh(\propto)\cos(\propto) + \cosh(\propto)\sin(\propto) + j[\cosh(\propto)\sin(\propto) - \sinh(\propto)\cos(\propto)]\} \tag{8}$$

$$Z_{21} = -\frac{\delta}{k}\{\sinh(\propto)\cos(\propto) - \cosh(\propto)\sin(\propto) + j[\cosh(\propto)\sin(\propto) + \sinh(\propto)\cos(\propto)]\} \tag{9}$$

where $\propto$ is defined as the ratio of the thickness to the penetration depth:

$$\propto = \frac{d}{\delta} \tag{10}$$

and the periodic penetration is calculated by using the following equation:

$$\delta = \sqrt{\frac{k.\tau}{\pi.\rho.C}} \tag{11}$$

where k is thermal conductivity (W/m.K), τ is period of variations (s), ρ is density (kg/m^3), and C is the specific heat capacity (J/kg.K). It should be noted that all these thermal parameters as well as thickness are known based on building materials used in this case. Thus, the elements of matrix were calculated based on Equations (7) to (9).

As a result, the heat transfer matrix from outside to the inside is:

$$Z_{out-in} = Z_{s2} \, Z \, Z_{s1} \tag{12}$$

where, Z_{s2}, Z_{s1} are the heat transfer matrices of inside and outside based on convection and radiation values. ISO 6946 described the standard value for R$_s$ [54].

$$Z_s = \begin{pmatrix} 1 & -R_s \\ 0 & 1 \end{pmatrix} \tag{13}$$

Finally, the time lag and decrement factors are calculated as follow:

$$\varphi = \frac{\tau}{2\pi} \arg Y_{12} \tag{14}$$

$$f = \frac{|Y_{12}|}{U} \tag{15}$$

When the Y_{12} is the periodical thermal transmittance as a function of the heat transfer matrix element (Z_{12} of Z_{out-in} matrix):

$$Y_{12} = -\frac{1}{Z_{12}} \tag{16}$$

2.5. Data Analysis

Samples collected by environmental equipment and information extracted from questionnaires were utilized as follows:

- Full-scale measurement: a daily average chart was depicted. The minimum, maximum and average and variance of each variable were identified. Charts were drafted in a line and box–whisker plot with Microsoft Excel. Explanatory information obtained in this step was used as input for Fanger's PMV-PPD model and energy usage calculation.
- Statistical analysis: statistical package for social science (SPSS)-IBM SPSS statistics 24- was employed to perform descriptive, frequency, one-way ANOVA, and regression.
- Cooling load design: the heat transfer through the building envelope was simulated using Energy 3D. The transient heat transfer equations were applied in Python to calculate time lag and decrement factor.

3. Results and Discussion

A critical analysis of collected data was carried out and the results are discussed in three sections as objective measurement, subjective measurement, and optimum temperature. The objective measurement represents the results of the analysis for thermal measurement and discusses them following similar studies or standards. The results of the survey analysis indicating occupant's thermal feedbacks and related analysis from the survey are given in the subsection of subjective measurement and have been discussed. The subsection suggests an optimum temperature to enhance thermal satisfaction and energy efficiency.

3.1. Objective Measurement

3.1.1. Air Temperature

Figure 6 shows the daily average air temperature (DAAT). Overall, DAAT shows a decrease during working hours, although the reduction is not significant. During this time, DAAT shows a low variance ranging from 23.6 to 24 °C with a mean of 23.8 °C

(Figure 6b). Low air temperature variance is an indication of a successfully applied mechanism to control indoor air temperature such as isolations that stop outdoor heat penetration to the indoor environment, resulting in a low air temperature variance. DAAT started at 24 °C and finished at 23.8 °C by 18:00 (Figure 6a).
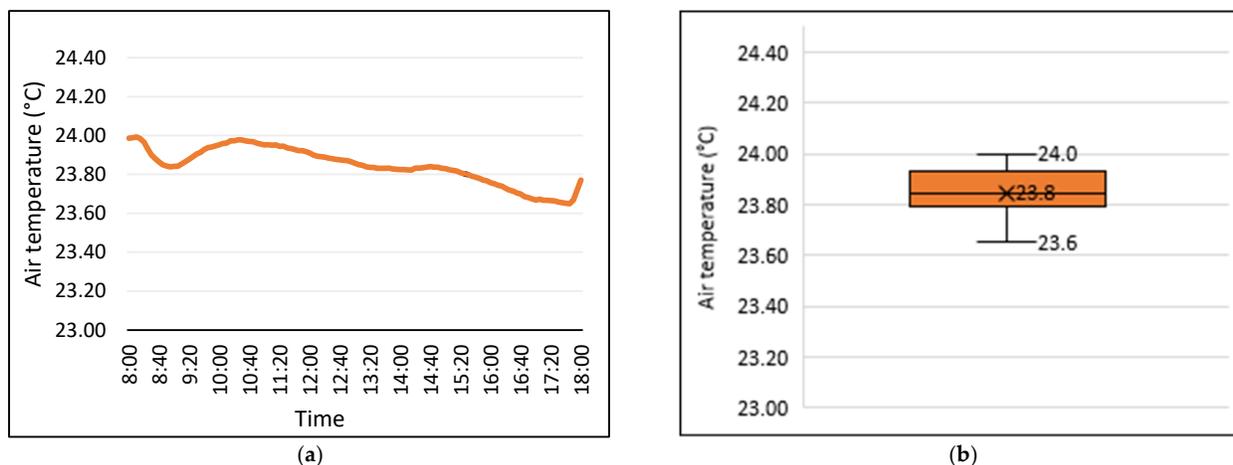

Figure 6. Daily average of air temperature (DAAT) and distribution. (**a**) DAAT; (**b**) distribution.

Air temperature samples were collected from different floors used for DAAT. To make sure there was no significant difference between collected samples of each floor, Kruskal–Wallis one-way ANOVA test was conducted. As shown in Table 6, statistically, there is a significant difference ($p < 0.05 = 0.000$) among mean air temperatures across floors. The main reason for this difference was observed to be occupant density, in which the fifth floor included a significantly higher number of occupants. In addition to occupant density, occupant control over the air vents could be another reason for this significant difference.

Table 6. Independent Kruskal–Wallis Test of mean air temperatures across floors.

Building	p Value
Case study building	0.000 *

* Significant if $p < 0.05$.

In general, air temperature is maintained around 24 °C, which is considered as an appropriate range according to MS 1525 [11]. Dry bulb temperature is recommended to be in a range of 24 to 26 °C with a minimum of 23 °C for office buildings [11]. ASHRAE Standard 55 [15] also suggests an upper limit of 27.2 °C (with 0.5 clo and 50% RH) to provide a thermally comfort zone for 80% of occupants. In addition, low air temperature is suggested to be associated with health issues such as respiratory disease and asthma [55].

3.1.2. Relative Humidity

Daily average relative humidity (DARH) is depicted in Figure 7a. Overall, RH reduced during building operation hours, with a considerable reduction in early hours. The early drop was due to the HVAC system operation schedule working between 8:00 and 18:00. The HVAC system was not operational outside of working hours, resulting in a rise of RH, and thus a drop in daily average RH can be seen by the start of working hours. The DARH started at 78% and reduced to 73% by 18:00. DARH ranged—without considering the outliners by the start of working hours—from 71% to 73%, with a mean of 72% (Figure 7b).
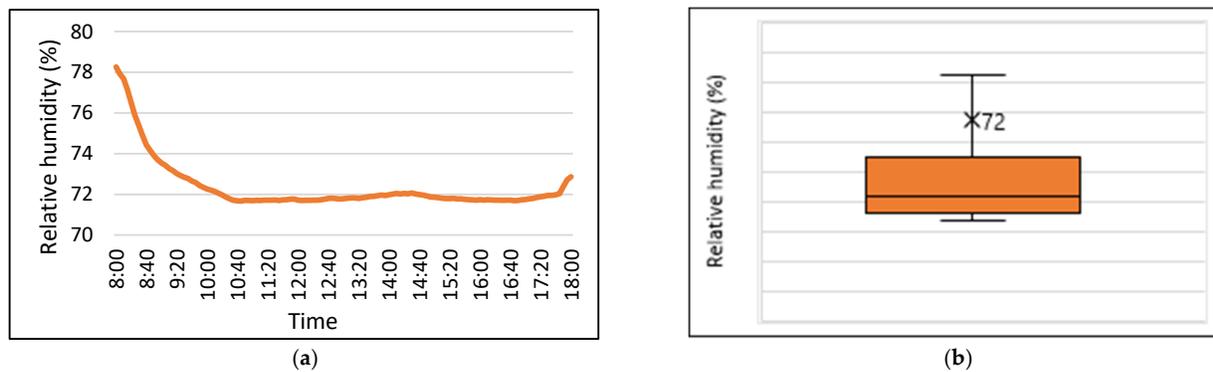
(**a**)

(**b**)

Figure 7. Daily average relative humidity (DARH) and distribution. (**a**) DARH; (**b**) distribution.

During the full-scale measurement, RH samples remained between 57% and 90%. Malaysian standard MS 1525 [11] suggests a range of 50% to 70% RH with an indication of not exceedingly more than 70% for office buildings. In this regard, average RH surpassed the suggested range. High humidity level was shown to have negative health effects for short-term exposure [56]. In addition, it is associated with bacteria, fungi, and virus growth in indoor environments [55].

3.1.3. Air Velocity

Figure 8a illustrates the daily average air velocity (DAAV). As mentioned in Section 2.2.1, air velocity is measured around the breathing area of a seated person during working hours. Holistically, DAAV shows a low and linear air velocity within the range from 0.04 to 0.06 m/s, with a mean of 0.05 m/s during working hours (Figure 8b). There is no vestige of any surprising increase or decrease. In addition, during monitoring, 0.03 and 0.09 m/s were the minimum and maximum data logged.
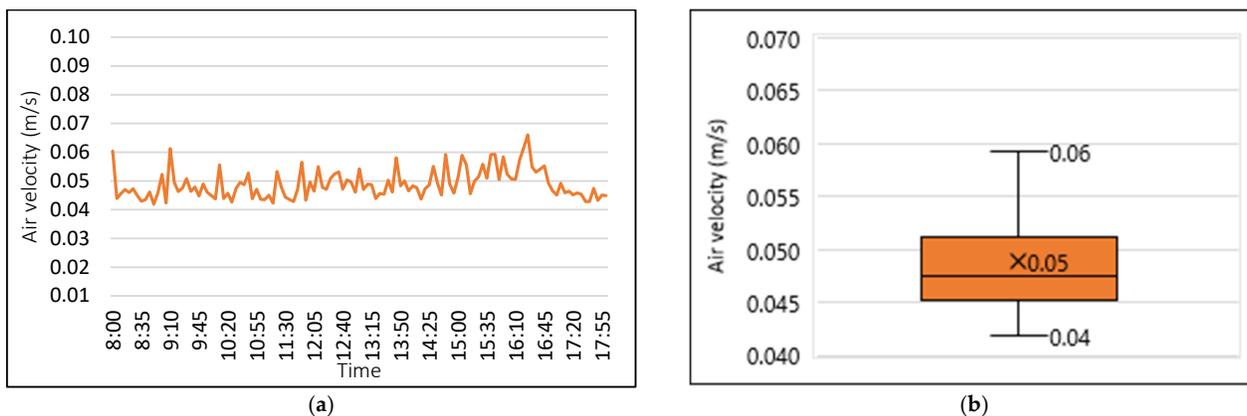

(**a**)

(**b**)

Figure 8. Daily average air velocity (DAAV) and distribution. (**a**) DAAV; (**b**) distribution.

Although the pattern observed in Figure 8a seems to shockingly change over time in airspeed, the low variance of 0.02 m/s was insignificantly felt by occupants. Lechner [57] indicated that air velocity below 0.05 m/s is notable by occupants. In addition, the maximum airspeed is suggested to be lower than 0.2 m/s by various standards, as reviewed by Khovalyg, Kazanci, et al. [58]. Malaysian standard MS 1525 [11] suggested a range from 0.15–0.50 m/s for air velocity. However, standards suggest that exceeding airspeed can be used in higher air temperatures (25 to 26 °C above) to have a thermally indoor environment [58]. In office buildings, controllable vents by occupants are highly suggested in exceeding air velocities to prevent papers from blowing away from the desk.

Particularly for this study, the building is equipped with adjustable vents to distribute air from the underfloor; however, it was observed that most of the vents adjacent to workstations were closed by occupants, which resulted in low air velocity near the breathing area of a seated person. This was due to the cool air temperature in which higher air velocity extended the level of cool sensation for occupants [58]. Thus, higher air temperature is suggested to convince occupants to allow more air flow around the breathing zone. This is an important implication since air change rate or airspeed contributes to overall air quality by removing pollutants from indoor air and improving work performance [55].

3.2. Subjective Measurement

3.2.1. Thermal Sensation Analysis

A questionnaire survey was used to evaluate variables of thermal quality. To do so, variables were evaluated with a seven-point Likert scale under ASHRAE Standard 55 [15] from uncomfortable (−3 to −1), neutral (0) and comfortable (+1 to +3). Figure 9 illustrates the distribution of the responses to overall comfort (a), thermal sensation vote (TSV) (b), temperature stability (c) and air humidity (d). Only a minority of occupants (22.6%) reported overall comfort—mean vote of 0.07—with thermal quality (Figure 9a). ASHRAE Standard 55 [15] suggests a minimum of 80% satisfaction from thermal quality, and the rate is critically lower in this building. The main reason for low satisfaction drives from a cool environment, as thermal sensation mean vote is −1.25 with 77.4% uncomfortable occupants (Figure 9b). Besides cool feeling, most occupants (81.1%) reported uncomfortable humid indoor air (Figure 9c). Both air temperature and relative humidity are significant variables contributing to thermal quality, which this building fails to satisfy in its occupants. A high RH level is also observed during monitoring of thermal quality (see also Figure 7). Regarding the stability of the air temperature, only a minority of occupants (24.5%) reported unstable air temperature during the day. This result is followed by low variance of air temperature during full-scale measurement (see Figure 6). Overall, the reports indicate that a majority are dissatisfied with thermal quality. This thermal unsatisfaction has been reported by other studies in tropical climates, resulting in proposed models to increase thermal quality [59], of which Fanger's PMV model is one of the tools to predict thermal satisfaction to improve quality of the variables.
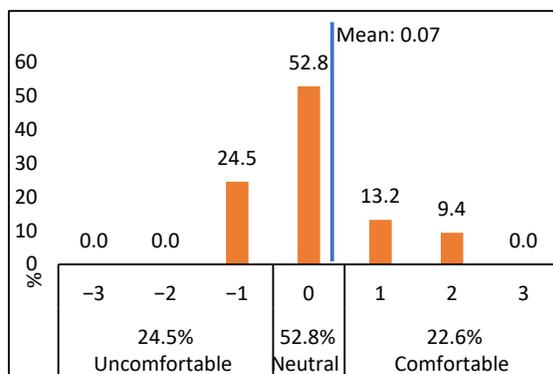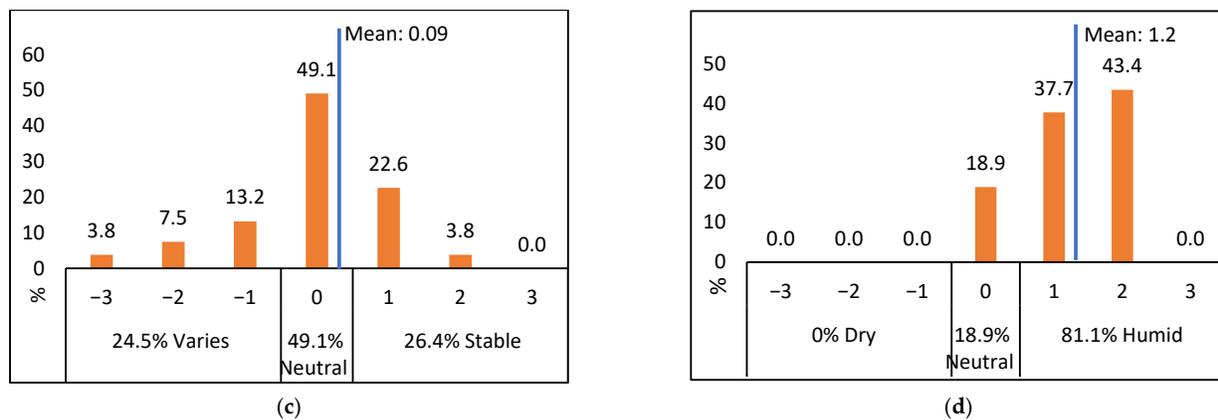

(**a**)
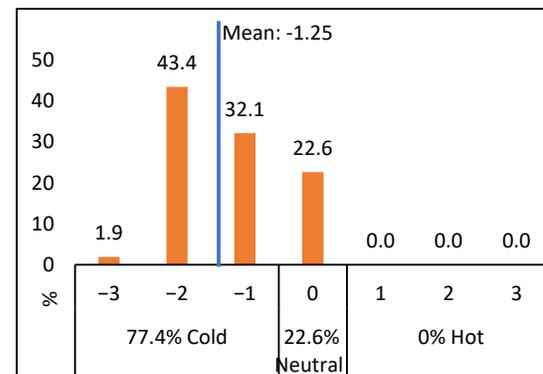
(**b**)

Figure 9. Frequency of occupants vote to thermal quality variables. (**a**) Overall thermal comfort; (**b**) thermal sensation vote; (**c**) temperature stability; (**d**) air humidity.

3.2.2. Thermal Analysis Based on Occupant Characteristics

Occupant responses for thermal variables were statistically analysed to determine whether there was a significant difference based on their characteristics. The characteristics were defined as age, gender, type of office, distance to a window, and work experience in building. *T* test and one-way ANOVA analysis results showed that statistically there is no significant difference ($p > 0.05$) between most variables (Table 7). Indicating, occupant responses were not affected by their characters. The responses are statistically different regarding the distance from the window over thermal sensation in which those far from the window reported cooler feeling versus those near the window. In addition, the overall thermal sensation was different according to the occupant's office type. In this regard, occupants in shared offices with more than eight people reported the highest satisfaction in thermal quality, whereas occupants in rooms shared with 2 to 4 people reported the lowest satisfaction (mean vote 4.88 to 3.86). Regarding gender, although Maykot and Rupp [23] reported a statistical difference according to gender over thermal comfort in an office building in the tropical climate of Brazil, there was no statistical difference observed in the finding of this study.

Table 7. Impact of occupant characteristics on the perception of thermal variables.

		Age		Gender			Type of Office			Near Window		Work Experience in Building	
		Under 30	Above 30	Male	Female	Private	2–4	5–8	N > 8	Yes	No	N < 1 Year	N > 1 Year
%		49%	51%	53%	47%	15%	41%	29%	15%	34%	66%	37%	63%
Overall thermal	t	−0.613		−2.334			F = 3.153			−0.118		−0.486	
	df	51		51			52			51		51	
	Sig	0.883		0.073			0.033 *			0.150		0.08	
Thermal sensation	t	0.534		0.703			F = 0.670			−0.491		0.032	
	df	51		51			52			51		51	
	Sig	0.347		0.515			0.574			0.002 *		0.450	
Humidity	t	−2.103		2.032			F = 1.891			1.099		0.935	
	df	51		51			52			51		51	
	Sig	0.213		0.544			0.143			0.517		0.616	
Stability	t	−0.502		−1.130			F = 0.125			0.485		0.226	
	df	51		51			52			51		51	
	Sig	0.481		0.059			0.945			0.592		0.359	

* Significant if $p < 0.05$.

3.2.3. PMV and TSV

Standards, such as the ASHRAE Standard 55 [15], provide guidelines to predict thermal comfort with the use of modes such as Fanger's PMV-PPD model. Comparisons of

Fanger's PMV-PPD with thermal sensation mean vote have been performed in various studies [59–61]. This comparison is usually performed to localize and upgrade accuracy in Fanger's PMV-PPD predictions. For this study, a comparison was made to: (1) investigate the accuracy of Fanger's PMV-PPD prediction for fully air-conditioned office buildings in a tropical climate, and (2) it was utilized to suggest neutral air temperatures. Based on the findings from full-scale measurements, the PMV-PPD model was calculated as shown in Table 8.

The PMV was −0.17, suggesting that the operational thermal condition complies with ASHRAE Standard 55 [15]. Thus, occupants should feel comfortable. However, PMV-PPD overestimated occupant thermal sensation, where TSV was −1.25 with a 1.8-unit difference in PMV prediction. ASHRAE Standard 55 [15] defined that the neutral thermal feeling for TSV is between −0.5 to +0.5. Any mean TSV out of this range is considered as not comfortable, leading to a higher percentage of thermal dissatisfaction.

Figure 10 illustrates the gap between PMV and TSV. Although PMV stays in the comfort zone, the TSV is out of the acceptable range according to ASHRAE Standard 55 [15]. A similar gap between PMV and TSV has also been reported in several studies over time [62–66]. In addition, it has been reported that the difference between predicted and actual sensation can be as large as 1.3 units [67,68]. According to Maiti [63], the difference could be due to the tropical climate of Malaysia. Maiti [63] stated that PMV predicted a lower neutral temperature for occupants, while TSV estimated a wider comfort zone and a higher neutral temperature for occupants. In addition, it is suggested that subjects were more sensitive to coldness in comparison to a warmer temperature. Studies have indicated that personal adaptations, such as physiological, psychological, or behavioural thermoregulation, were not included in the PMV model as a parameter, which can be the reason for the PMV overestimation [69–71]. Thus, other implications need to be considered for providing a thermally comfortable environment, such as a regional thermology specification that is profoundly influenced by the local climatic condition, food, habitat, socio-culture, etc.

Table 8. Thermal comfort prediction—based on the average value measures.

	T_a (°C)	T_r (°C)	R_h (%)	V_a (m/s)	M_e (met)	Cl (Clo)	PMV	TSV	Thermal Sensation
Case study Building	23.8	23.8	72.35	0.05	1.1	0.57	−0.17	−1.25	Neutral

Clo: for typical office type [72]; M_e: normal activity of office typing [72]; $T_a = T_r$ [26,73].
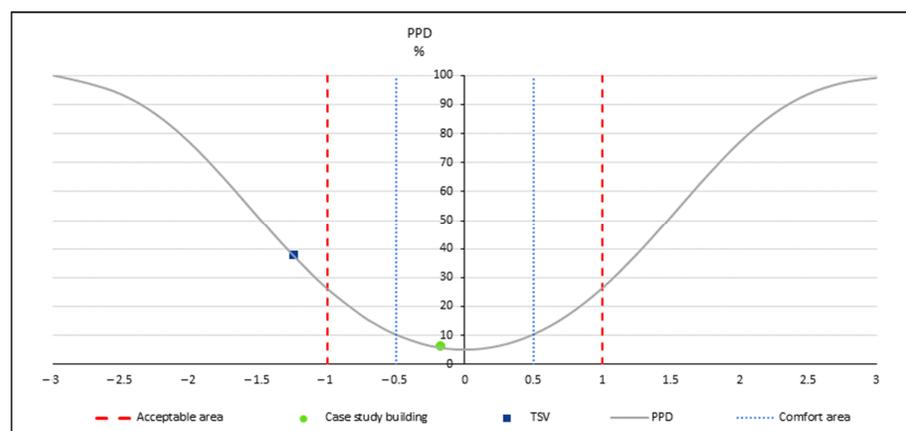

Figure 10. TSV versus Fanger's PMV-PPD model.

3.3. Temperature (T_{opt}) Optimization

The low set-point of the HVAC system causes extra power consumption and occupant comfort reduction. According to the literature, adjusting the thermostat temperature of the HVAC system is the best strategy to optimize thermal comfort [74]. Due to the critical condition of thermal quality based on the occupant's report indicating highly negative TSV, different models of neutral temperatures are suggested using the PMV-PPD model. The overestimation of Fanger's PMV model identified in this study is also considered to suggest neutral air temperatures. Air temperatures are measured as neutral if complying with the ASHRAE Standard 55 [15]. Air velocity and relative humidity are considered fixed items in the PMV model variables. Input data for the model is driven from the full-scale measurement result. Concerning negative TSV (−1.25), neutral temperatures should be higher than the mean temperature (23.8 °C). To find neutral values, the input air temperature in the model can start at 24.0 °C, with a 0.5 °C interval increase. This increase is limited to when the model fails to comply with SHRAE Standard 55 [15] and/or EN 16798-1 [14].

Table 9 presents PMV-PPD results for different temperatures. Model 0 predicts PMV-PPD based on real-world data (≈24.0 °C). As shown in Table 9, Models 1, 2 and 3 comply with ASHRAE Standard 55 [15], indicating that, with an increase in air temperature from 24.0 to 25.5 °C, occupants should feel comfortable with around 8% PPD. Dissatisfied occupants should have a slightly warm sensation within Models 1 to 3. This indicates a potential shift in occupants' thermal sensation vote from slightly cool to slightly warm. Model 4, with 26 °C air temperature, fails to comply with ASHRAE Standard 55 [15]. Temperatures higher than 26 °C do not comply with standards, which can predict a high percentage of unsatisfied occupants. In addition, a temperature of above 26 °C is reported to associate with lower productivity in office buildings [58].

Table 9. PMV-PPD for different neutral temperatures.

Models	T_a (°C)	T_r (°C)	R_h (%)	V_a (m/s)	M_e (met)	Cl (Clo)	PMV	PPD (%)	Thermal Sensation
Model 0	24	24	72.35	0.05	1.1	0.57	−0.11	6	Neutral
Model 1	24.5	24.5	72.35	0.05	1.1	0.57	0.06	5	Neutral
Model 2	25	25	72.35	0.05	1.1	0.57	0.23	6	Neutral
Model 3	25.5	25.5	72.35	0.05	1.1	0.57	0.39	8	Neutral
Model 4	26	26	72.35	0.05	1.1	0.57	0.56	12	Neutral

Complies with ASHRAE Standard 55-2017: Model 1–3. Complies with EN-16798-1: Model 1–4.

To have an optimum air temperature based on thermal comfort and energy efficiency, cooling energy consumption for the suggested models is calculated. In addition, considering PMV overestimation, it can be deduced that Model 4 with 26 °C—with 0.5 °C difference compared to Model 3—is acceptable for occupants in the real world.

The energy calculation allows investigating the potential of energy saving for cooling the indoor environment. Average measured indoor air temperature versus outdoor temperature is shown in Figure 11. The measured temperatures indicate that, although outdoor temperature increases, the indoor temperate stays in a constant range around 24 °C. which means that the HVAC system consumes more energy in hotter hours in order to maintain indoor air temperature.
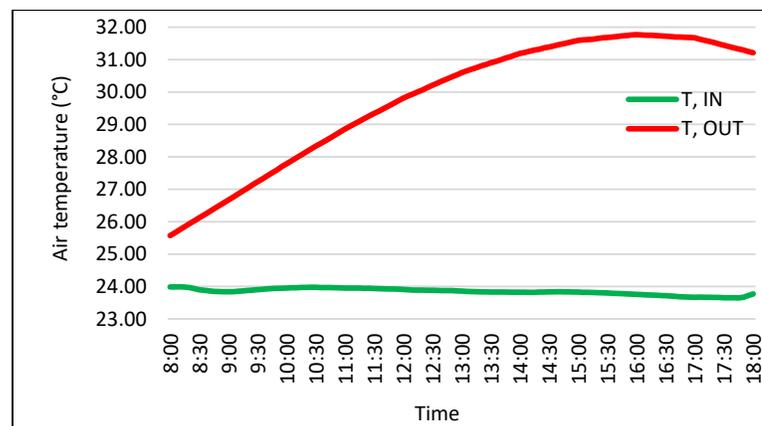
Figure 11. Indoor vs. outdoor temperature.

The building's facade is a double-glazed curtain wall (low-E glass double-glazed curtain) in the south and east to allow daylight penetration. The north and west sides of the building were constructed using reinforced concrete with minimum openings. The roof was covered by turf to minimize solar heat gain (U value of 0.43). Heat conduction through walls and windows was calculated by applying Equations (1) to (15). The equations were implemented in Python. Figure 12 shows that the schematic heat transfer through this building envelopes at 4 p.m. on 1 July.
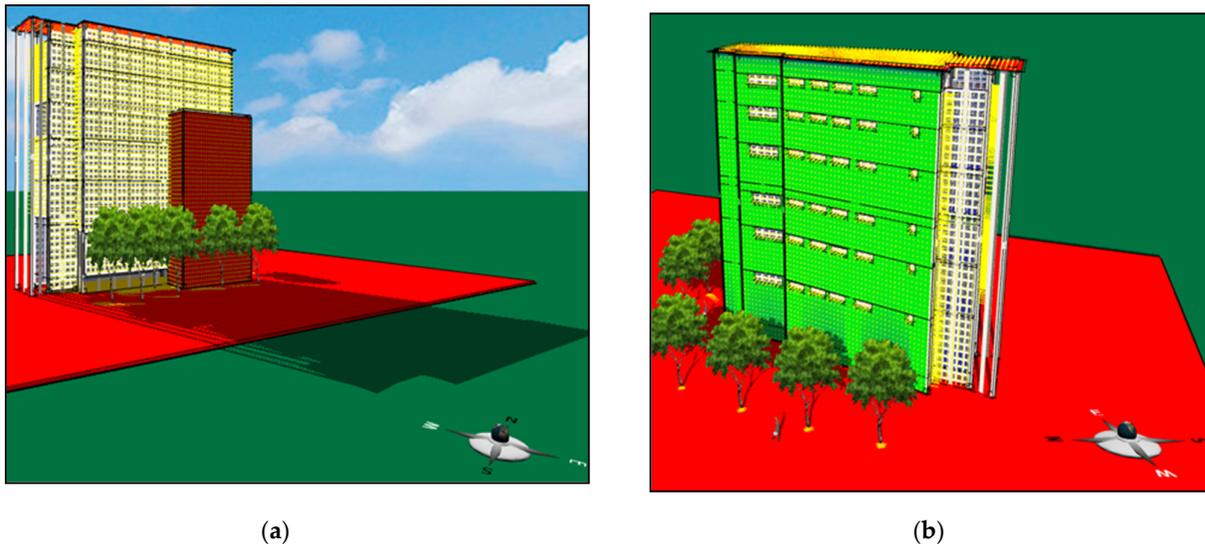

(**a**)   (**b**)

Figure 12. Schematic of heat transfer. (**a**) East view; (**b**) north view.

The solar heating gain coefficient (SHGC) of glazing in the west and east facades is around 0.37, and in the north and south facades, it is 0.46, with an emissivity of 0.16 and a U value of 0.95. According to Equation (4), the solar-air temperature was estimated by a sinusoidal model to calculate TETD. The calculated temperature for 24 h in Kuala Lumpur is shown in Figure 13. The comparison between calculated T_{sa} and measured T_{out} (Table 10) shows that the calculated sol-air temperatures are in good agreement with the outdoor temperature.
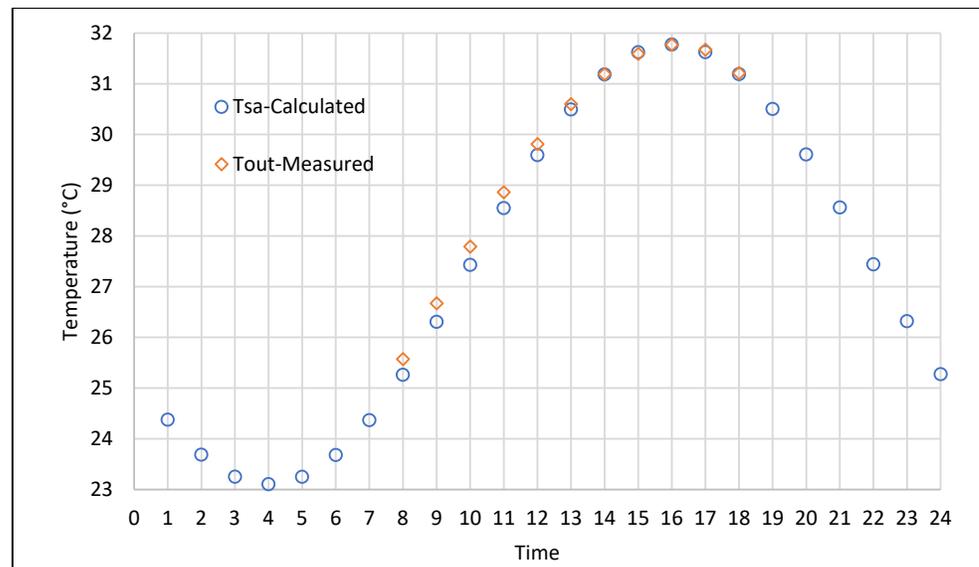
Figure 13. Sol-air and outdoor temperature.

Table 10. Pearson's correlation between T_{sa} and T_{out}.

Time	T_{sa} Calculated	T_{out} Measured	Correlation	
			Pearson Correlation	**Sig. (Two-Tailed)**
8	25.25	25.57		
9	26.30	26.67		
10	27.42	27.79		
11	28.54	28.86		
12	29.59	29.81		
13	30.49	30.60	1.000 **	0.000
14	31.18	31.19		
15	31.61	31.59		
16	31.77	31.77		
17	31.62	31.67		
18	31.18	31.21		

** Correlation is significant at the 0.01 level (two-tailed).

The time lag and decrement factor of roof, walls, and windows were determined based on EN-ISO 13786 [53]. Thus, $T_{sa,\varphi}$ was calculated according to the results. Then, the TETD of the roof, concrete walls and curtain walls was determined based on Equation (2) (Figure 14). This led to calculating the amount of heat transfer through conduction in different temperatures. As indicated in Figure 15, the cooling load can be reduced by increasing the set-point temperature during working hours in this office. As shown in Figure 16 the cooling power can be reduced by around 30% at 5 p.m. by increasing the set-point temperature to 26 °C.
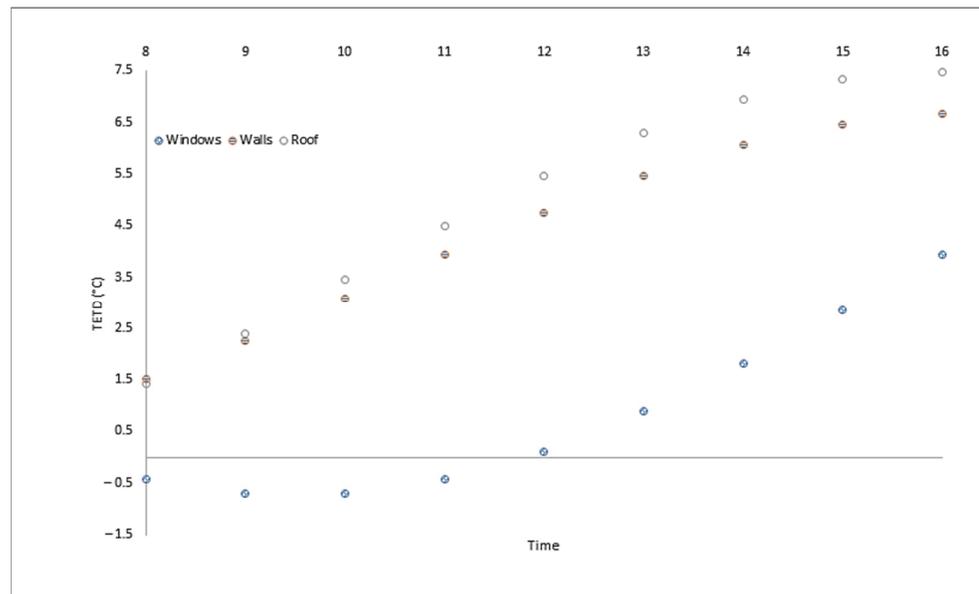
Figure 14. TETD of building envelopes at 24 °C.

Total external cooling load is a function of both conduction and radiation heat transfer. The main radiation occurs through windows, which can be calculated by the following equation:

$$Q = A.\,SC.\,ES.\,CF.\,SF \qquad (17)$$

where A is the heat transfer area (m²), SC is shading coefficient, ES is external shading coefficient, CF is a correction factor for different orientations, and SF is the solar factor W/m² = 194 for Malaysia. Thus, the total external cooling load was determined for this building. The findings show that energy consumption tends to decrease with an increase of set-point temperature (Figure 16). In addition, the neutral temperature is at 24.3 °C, with a cooling load of 1427.8 kW (Figure 16). As shown in Figure 17 the intersection points between PMV and cooling power is at 24.9 °C. At this point, the PMV is 0.2, PPD is 6%, and cooling power is 1262.3 kW. It reveals that by 0.6 °C increments in set-point temperature, energy usage reduces around 11.6%, and PPD increases by 1%. Furthermore, the cooling power decreases 36% by setting the indoor temperature to 26 °C. This point is the minimum of the cooling power, with an acceptable PMV-PPD.
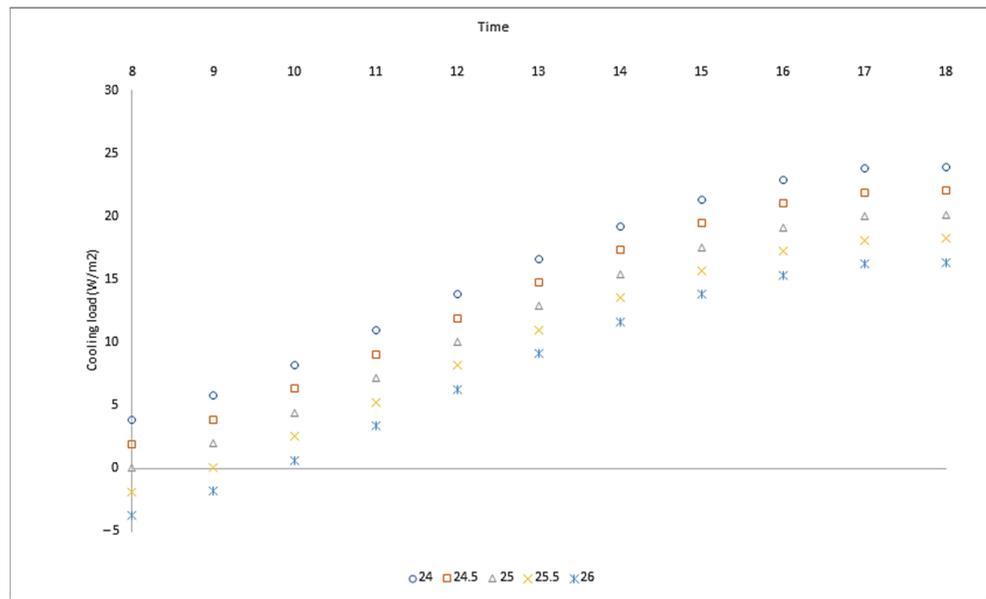
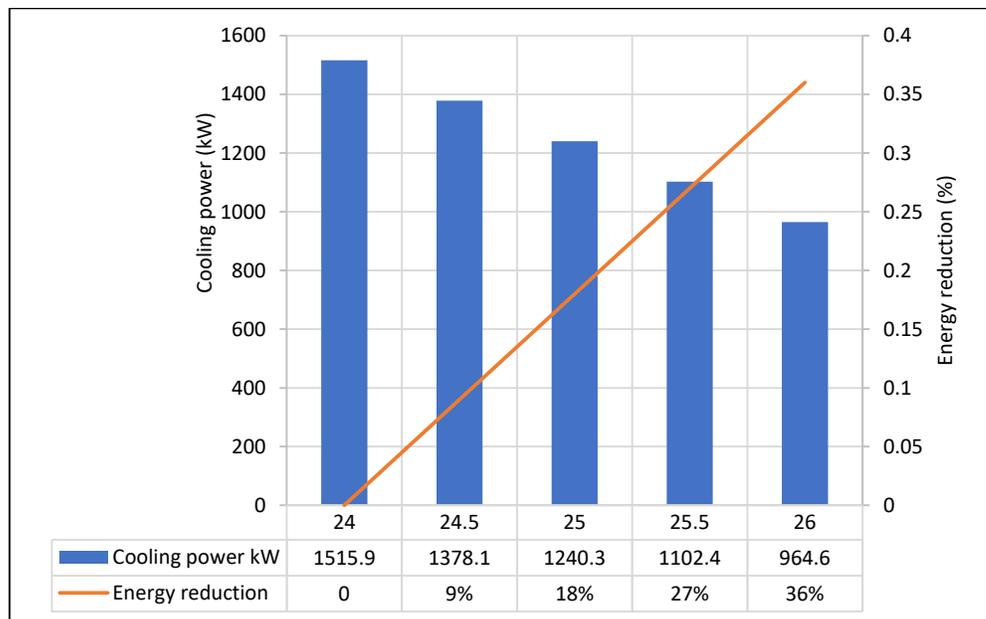**Figure 15.** Hourly cooling load in different temperatures.

	24	24.5	25	25.5	26
Cooling power kW	1515.9	1378.1	1240.3	1102.4	964.6
Energy reduction	0	9%	18%	27%	36%

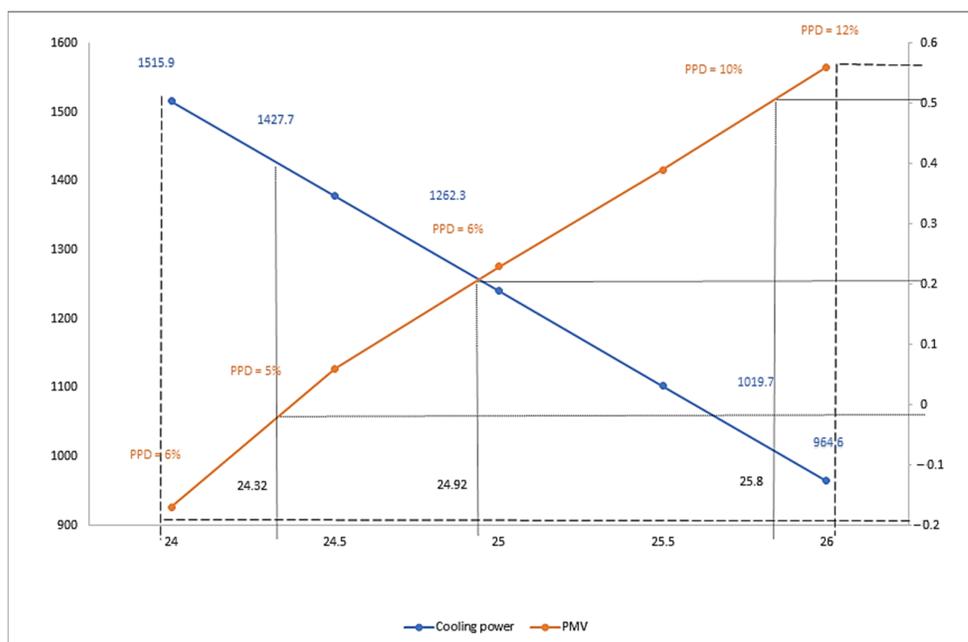**Figure 16.** Total cooling load in different temperatures.

Figure 17. Optimum temperature based on PMV and cooling power.

Concerning cooling load demand, green construction aims to meet energy-saving policies at international, national, and regional levels. The findings indicate overworking of the HVAC system increases the cooling load in contrast to green construction goals. Although the building under this study was considered energy efficient, the findings implied overworking of the HVAC system resulted in thermal dissatisfaction. Thus, an increase of air temperature from 23.8 to 26 °C is suggested to reduce cooling load by up to 36% annually and to improve thermal satisfaction. Similarly, a study by Aynsley [75] suggested the following equation to predict the neutral temperature based on outdoor dry bulb temperature in Southeast Asia.

$$T_n (\pm 3.5\ °C) = 17.6 + 0.31\ T_m \tag{18}$$

Using Equation (18), the neutral temperature for Kuala Lumpur, with a mean temperature of 28 °C is 26.2 ± 3.5 °C. This is in alignment with the suggestion of this study. In addition, the proposed temperature by other studies in this region is summarized in Table 11.

Table 11. Comparison of neutral temperatures.

Location	Type of Building	Temperature (°C)	Reference
Malaysia	GBI Office building	26	This study
Singapore	Office and Residential	24.2	De Dear and Brager [76]
Indonesia	Office	26.7	Karyono [77]

4. Conclusions

This study aimed to investigate: (a) thermal quality and (b) energy cooling demand to optimize thermal satisfaction and energy efficiency for a GBI Platinum-certified office building in Malaysia within a tropical climate. The filed investigation was taken into action to investigate thermal quality subjectively and objectively. The subjective investigation included a questionnaire survey and measurement of air temperature, relative humidity, and air velocity as objective investigations. To calculate cooling energy demand, the TETD method was applied to the study with the utilization of Python to calculate the

equations. Fanger's PMV-PPD model was also applied to suggest a range of neutral air temperatures.

The findings indicated that 77.4% of occupants reported cool thermal sensation, with only 22.6% reporting overall thermal comfort. Statistical analyses revealed that there is no significant thermal difference according to gender, but office type made a significant difference for thermal sensation. Measuring thermal variables showed an average air temperature of 23.8 °C, average high relative humidity of 72%, and low air velocity with a mean of 0.05 m/s. Under these circumstances, the mean TSV was observed to be −1.25, indicating cool sensations out of the acceptable range. This finding highlighted the overworking of the HVAC system, resulting in extreme energy consumption.

To optimize the air temperature according to cooling load and thermal satisfaction, Fanger's PMV-PPD was employed to predict neutral air temperatures with consideration of the overestimation observed between PMV and TSV. Besides, the cooling load demand is calculated for various air temperatures, which indicated a 36% cooling load energy reduction by rising the cooling setpoint to 26 °C indoor air temperature. Under this, the occupant's thermal satisfaction can be increased, while the cooling energy demand can be reduced.

Providing a thermally comfortable indoor environment for green buildings can be challenging in Malaysia due to the hot tropical climate. The cooling indoor environment needs a considerable amount of energy or special methods of design with natural ventilation to provide a thermally comfortable indoor environment. Thus, the conflict between energy-saving and occupant thermal satisfaction needs special attention to meet green building objectives, while maintaining a thermally comfortable indoor environment. Findings of this research demonstrated that delivering a thermally comfortable indoor environment to satisfy occupants requires more in-depth and sociological investigation, rather than just complying with ISO/OSHA standards. These findings can be utilized to improve universal and local standards and policies related to thermal comfort and energy consumption particularly related to tropical climate. Finally, this study provided new knowledge on occupant satisfaction from thermal quality and introduced new findings on building performance by proposing an optimum air temperature for a tropical climate.

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