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Determination of Thermal Comfort Zones through Comparative Analysis between Different Characterization Methods of Thermally Dissatisfied People

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Abstract: In order to maintain thermal comfort and preserve indoor environmental quality, people use heating, ventilation and air-conditioning (HVAC) systems inside buildings. However, buildings must be prepared not only to provide adequate thermal comfort to their occupants but also to align strategies that enable better energy performance. Thus, this work aimed to establish thermal comfort zones (TCZ) through different characterization methods of thermally dissatisfied people. Responses were collected from 481 students, through the application of questionnaires in classrooms, during the Brazilian winter of 2019. Three methods for determining the actual percentage of dissatisfied (APD) were adopted, which generated three different equations, namely: APD_1; APD_2 and APD_3, based on the original Predicted Percentage of Dissatisfied (PPD) equation. By using the probit model, three TCZ were calculated: 17.73–22.4 °C (APD_1); 20.71–20.93 °C (APD_2) and 17.89–24.83 °C (APD_3). In addition, a comfort zone based on the linear regression between the thermal sensation votes and the operative temperature was determined (18.77–22.69 °C). All thermal comfort zones resulting from this work have colder temperatures than that indicated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers—ASHRAE (2017) of 23–26 °C for the winter, showing the potential for energy savings from the adoption of this type of strategy, while maintaining thermal comfort.

Keywords: thermal comfort predicted mean vote; predicted percentage of dissatisfied; actual percentage of dissatisfied; thermal comfort zones; statistical modeling

Citation: Pereira, P.F.d.C.; Broday, E.E. Determination of Thermal Comfort Zones through Comparative Analysis between Different Characterization Methods of Thermally Dissatisfied People. *Buildings* **2021**, *11*, 320. https://doi.org/10.3390/buildings11080320

Academic Editors: Thomas Parkinson and Marcel Schweiker

Received: 18 June 2021
Accepted: 22 July 2021
Published: 26 July 2021

1. Introduction

Indoor Environmental Quality (IEQ) refers to the excellence of internal parameters, such as indoor air quality, visual comfort, acoustic comfort and thermal comfort [1,2]. While IEQ is of utmost relevance to occupants, buildings must be prepared not only to provide comfort to their users but also to operate efficiently, as buildings account for approximately one-third of total energy consumption throughout the world [3].

In some countries, this reality becomes more effective; so, regulating consumption has significant potential for energy savings [4]. According to Zhao et al. [5], more than one-third of China's local energy consumption comes from buildings, of which 63% is due to cooling or heating systems. In another research performed by Li et al. [6], in the same country, energy consumption has increased by 45% in the last 20 years. Indraganti et al. [7], comment that in India, from 2004 to 2010, there was a significant increase of 13.4% in energy consumption, which is in line with the reported energy shortage across the country, with the construction sector being one of the most responsible. Kumar et al. [8] highlighted in their work that urban India, due to economic prosperity, will have a substantial growth in the use of mechanical air conditioners.

According to Buratti et al. [9], Li et al. [10] and Noversa et al. [11], the integration of the ISO 7730 [12] evaluation method into the most economical HVAC system simulation codes aims to evaluate thermal comfort level in terms of the Predicted Mean Vote (PMV). This index aims to identify the relationship between the subjective feeling of comfort. As thermal comfort can be defined as the combination of the psychological state that expresses satisfaction with the thermal environment and neutral thermal balance of body temperature as a whole, it is very difficult to satisfy everyone in the same environment. For this condition, the standard ASHRAE 55 [13] states that the environmental conditions that result in thermal comfort are not the same for everyone and provide comfort temperature ranges called Thermal comfort zones (TCZ).

The thermal comfort zone in an environment is the one in which most people, due to certain environmental conditions, will be in thermal comfort, and this is one of the most relevant strategies for energy saving [14,15]. Typically, these zones provide 80% acceptability by occupants, that is, 20% dissatisfied, consisting of 10% of users thermally dissatisfied due to physiological conditions plus an additional 10% dissatisfied due to localized discomfort. Thus, the comfort zone is defined by the combination of six thermal comfort variables for which the PMV is within the limits presented within the category B of ISO 7730 [12]: $PPD < 10\%$ and $-0.5 < PMV < 0.5$. According to ASHRAE 55 [13], the TCZs for summer and winter are 20–23 °C and 23–26 °C, respectively. The operative temperatures are 22 °C in summer and 24.5 °C in winter.

Djongyang, Tchinda and Njomo [16] state that these thermal comfort zone configurations were assumed for: a relative humidity of 50%; an average air velocity below 0.15 m/s; a mean radiant temperature equal to the air temperature; a metabolic rate of 1.2 met and a clothing insulation of 0.9 clo in the winter and 0.5 clo in the summer.

The adoption of standardized parameters can help to optimally reconcile the relationship between human thermal comfort and energy efficiency. However, Mui, Tsang and Wong [17] point out that the simple use of models, without due attention to the discrepancies generated between data predicted by the model and data obtained in field studies, significantly affects the implication of energy savings in thermal comfort research. Van Hoof [18] explains that the discrepancies observed might be due to the type of ventilation in the building, the small number of individuals who may have a large inter-individual distribution in thermal preferences, different climates, types of construction, age group, among others. This observation is relevant for studies on thermal comfort, as it indicates the importance of local studies to determine the best conditions for each type of indoor environment.

Oseland [19] reported that there are significant discrepancies between the predicted mean vote (PMV) and actual mean votes (AMV) obtained in offices and homes, compared to climate chamber studies, attributing the differences to the contextual effects. Han et al. [20] explain that real environments can hardly be replicated in climatic chambers, which can cause concern when standards are applied to residents who live in real-world situations. Thus, data obtained in field studies reflect the particular behavior of a sample in a given environment in relation to thermal comfort and better represent its preferences [21].

For this reason, some studies choose to use the actual percentage of dissatisfied (APD) [22–25]. According to Yao, Liu and Li [23], APD is the percentage of votes on the ASHRAE [13] seven-point thermal sensation scale determined as votes of dissatisfaction at a given air temperature in the field survey. Knowing the percentage of real dissatisfied people is essential for the correct dimensioning of HVAC systems. When comparing the PMV and AMV scores, it is possible to find differences in the operative temperature and to calculate the best TCZ for a given environment and, consequently, it will be possible to reduce energy consumption through the correct adjustment of the temperature range [24].

Hwang et al. [25] highlighted the relevance of the integration between APD and TCZ when they discovered that only 40% of hospital environments they analyzed were within the comfort zones recommended by ASHRAE [13]. This research gap was demonstrated by Park and Nagy [26] and Kim et al. [27], where the authors emphasize the importance of exploring and understanding both the thermal sensation and the comfort zones to maximize energy savings. In view of the relevance of this subject, this work aims to determine thermal comfort zones through a comparative analysis between different methods used by thermally dissatisfied people.

2. Background

Table 1 shows all alternative equations for the percentage of dissatisfied people obtained in field studies, based on the real thermal sensation vote (TSV) or operative temperature. Country, sample, type of ventilation and minimum percentage (PPD_{min}) are also highlighted. In total, 16 works are presented.

Table 1. Alternative models for the predicted percentage of dissatisfied.

Reference	Country	Sample	Type of Ventilation	PPD	PPD_{min} (%)
[28]	Portugal	48 women	HVAC	$APD = 100 - 67.8297 \exp[(0.40454\ AMV^4 - 1.51038 AMV^2)]$	52.31
[29]	Germany	n/a	n/a	$PPD = 100 - 84.3 \exp[0.01(PMV - 0.4)^4 + 0.5479(PMV - 0.4)^2]$	16
[30]	China	n/a	n/a	$PPD = 11.37PMV^2 + 18.34PMV + 24.42$	18
[31]	Brazil	n/a	n/a	$PPD = 100 - 52.5 \exp(-0.03353PMV^4 + 0.2179PMV^2)$	47.5
[32]	Brazil	1200	n/a	$PPD = 18.945\ TSV^2 - 0.24TSV + 25.41$	25.4
[33]	China	120 participants	n/a	$PPD = 9.1706MTS^2 - 8.9396MTS + 9.6263$	7.5
[34]	Taiwan	22 college students	HVAC	$APD = 100 - 84 \exp[-0.00051\ (TSV + 0.4)^4 - 0.1401\ (TSV + 0.4)^2]$	16
[35]	Taiwan	968	HVAC	$PD = 100 - 91.1 \exp[-0.00367(TSV + 0.45)^4 - 0.11135\ (TSV + 0.45)^2]$	9
[36]	China	87 elderlies	HVAC	$PPD = 100 - 97 \exp(-0.3338MTSV^2 - 0.01972MTSV^4)$	3
[37]	India	40 college students	HVAC	$PPD = 112.35953 - 107.395 \exp(-0.173587(TSV - 0.53175)^2)$	13.47
[38]	Italy	4000 students	NV	$PDacc = 100 - 85 \exp(-0.131\ TSV^4 - 0.285\ TSV^2)$	15
[39]	Malaysia	293 employees	HVAC	$APD = 1.0931To^2 - 56.092To + 735.22$	n/a
[40]	Australia	28 college students	HVAC	$PPD = -0.0074TSV^3 + 0.1101TSV^2 + 0.0471TSV$	n/a
[41]	Poland	50 students	HVAC	$PD = 100 - 99.9 \exp(-0.0355PMV^4 - 0.242PMV^2)$	0
[42]	China	110 college students	HVAC	$PPD = 730.55 - 728.29 \exp(-0.025\ TSV^2 + 0.003\ TSV - 0.00009)$	2.26
[43]	China	442	HVAC	$APD = 519 - 41.93To + 0.85To^2$	5

n/a = not available.

The main motivation that guides studies to propose new PPD curves based on the actual percentage of dissatisfied (APD) is to try to somehow correct the Fanger model. Hwang et al. [34,35], when performing their study, cast doubt on whether the PMV/PPD model is suitable for Taiwan's heat and humidity. As well as D'Ambrosio Alfano et al. [38] for the Mediterranean climate and Yau and Chew [39] for hot and humid climates. Hwang and Chen [36] were motivated by the doubt that the predictive model was qualified to satisfactorily predict the response of a specific audience, in the case of the elderly. Maiti [37] did the same when it was tested whether the PMV was good for the Indians or not. Chong et al. [42] tested whether acclimation to short-term heat acclimation was an effective method for increasing occupant acceptance of hot environments. Zhang, de Dear and Candido [40] tested temperature cycles induced by direct charge control strategies and proposed a curve of dissatisfied.

Piasecki et al. [41] tested the reliability of Fanger's thermal comfort model through a case study in an office with nearly zero-energy buildings (NZEB), while Wu et al. [43] assessed the potential for energy savings in 11 office buildings with split air-conditioning. The highest PPD_{min} (%) was presented by Araújo and Araújo [31] and Broday and Xavier [28], with 47.5% and 52.31%, respectively. Both authors adopted the perspective that only those participants who voted 0 on the seven-point scale would be satisfied with the thermal environment. The patterns from ASHRAE [13] determine TCZ for PPD < 10% and $-0.5 < PMV < 0.5$, as shown in Table 2.

Table 2. TCZ ASHRAE.

Season	Thermal Comfort Zone	Operative Temperature
Summer	20–23 °C	22 °C
Winter	23–26 °C	24.5 °C

Table 3 summarizes the main thermal comfort zones obtained in recent years in field studies, all values included were calculated based on ISO 7730 category B (80% thermal acceptability).

Table 3. Alternatives Thermal Comfort Zones.

Reference	Country	Climate	Season	Construction Type	Type of Ventilation	Sample	TCZ Calculated (°C)	Neutral Temperature (°C)
[44]	Australia	subtropical	Summer	Classrooms	HVAC and NV	2850 students	19.5–26.6	22.5
[20]	China	hot-humid	Summer	Residences	HVAC and NV	111 people (average 41.8 years old)	22.0–25.9	28.6
[28]	Portugal	Mediterranean	Winter	Office	HVAC	48 women	19.61–22.61	21.1
[33]	China	Dry	Winter	Residential buildings	n/a	120 people (14–80 years)	18.0–25.5	20.9 (men) 21.9 (women)
[34]	Taiwan	hot-humid	n/a	laboratory chamber	HVAC	22 college students	23.0–28.0	n/a
[35]	Taiwan	hot-humid	n/a	workplaces and residences	HVAC	968 data	20.4–28.4	25.9
[36]	China	n/a	Summer and Winter	Residences	HVAC	87 elderly (average 71 years old)	23.2–27.1 (summer)	25.2 (summer) 23.2 (winter)
[37]	India	n/a	n/a	conference room and laboratory room	HVAC	40 college students	23.25–27.18	24.83
[39]	Malaysia	hot and humid climates	n/a	Hospital	HVAC	293 employees	19.2–28.5	23.8
[42]	China	subtropical	Summer	Climate chamber	HVAC	110 college students	23.5–29.1	n/a
[43]	China	Hot summer cold winter (HSCW)	Summer and Winter	Office	HVAC	442 occupants	24.6–28.6	26.7
[45]	Indonesia	hot-humid tropical	n/a	Office	HVAC and NV	596 workers (19–53 years)	23.5–29.9	26.7
[46]	China	continental subtropical monsoon humid climate	Spring	Classrooms	NV	1273 students (average 20 years old)	17.0–30.0	21.5
[47]	China	subtropical	Summer and Winter	Office	HVAC	422 people	22.5–24.7 (summer) 20.2–23.6 (winter)	23.6 (summer) 21.4 (winter)
[48]	China	subtropical monsoon humid	Summer	Buildings	HVAC and NV	229 occupants	25.0–31.6 (NV) 25.1–30.3 (HVAC)	28.3 (NV) 27.7 (HVAC)

Table 3. *Cont.*

Reference	Country	Climate	Season	Construction Type	Type of Ventilation	Sample	TCZ Calculated (°C)	Neutral Temperature (°C)
[49]	Indonesia	hot-humid tropical	n/a	Classrooms	NV	20 students	23.9–27.0	25.4
[50]	India	Composite Climate	Summer and monsoon	Building apartments	NV	113 occupants (average 42 years old)	26.0–32.5	29.2
[51]	India	Dry	Summer	Residential Buildings	NV	113 occupants (17–69 years)	27.3–33.1	30.2
[52]	Korea	oceanic temperate climate	Spring and Fall	Classrooms	n/a	962 students (average 24.3 years old)	17.0–25.0	n/a
[53]	Italy	n/a	Summer and Winter	Open plan offices	HVAC	145 subjects	21.5–24.5	n/a
[54]	China	Dry	Summer and Winter	residential buildings	n/a	76 subjects	13.6–32.4	18.9 (winter) 23.3 (summer)
[55]	Malaysia	Tropical	n/a	Hospital	n/a	188 subjects	21.2–25.5	23.4
[56]	Malaysia	Tropical	n/a	Museum	HVAC	28 subjects (average 23.71 years old)	18.0–22.0	22.5
[57]	China	Subtropical	Summer	urban spaces	NV	2089 subjects (average 25.7 years old)	25.3–32.3	28.6
[58]	India	hot and humid climates	Spring and Fall	Classrooms	NV	82 students	22.1–31.5	29.0
[59]	India	hot-humid subtropical (1) cold (2)	All seasons	University	NV	325 subjects (average 20.3 years old)	12.5–32.3	29.7 (1) 21.2 (2)
[60]	Madagascar	Tropical	n/a	Hospitals, Shopping center, traditional buildings, schools	HVAC	1092 people	22.9–27.2	n/a
[61]	Korea	n/a	Summer	Apartment	HVAC	50 occupants	24.7–28.3	n/a
[62]	India	hot summer monsoon with dry winter	Monsoon and winter	Classrooms	NV	130 students	15.3–33.7	27.1
[63]	Romania	temperate	n/a	Office and residential buildings	NV	738 subjects	22.6–26.0	n/a

Table 3. *Cont.*

Reference	Country	Climate	Season	Construction Type	Type of Ventilation	Sample	TCZ Calculated (°C)	Neutral Temperature (°C)
[64]	China	Subtropical	Summer and Winter	office building	HVAC	656 questionnaires	22.1–29.6	23.3
[65]	Hong Kong	hot-humid subtropical	Summer	Classrooms	HVAC	982 students	21.56–26.75	24.0
[66]	India	Composite Climate	Summer and Winter	Classrooms	NV	1.890 children and teenager (10–18 years)	16.0–33.7	28.2 (Summer) 19.4 (Winter)
[67]	Colombia	tropical	n/a	Office	NV	72 people (20–60 years)	19.97–26.9	23.47
[68]	China	Subtropical	Winter	Classrooms	NV	992 college students (17–22 years)	19.5–21.8	20.6
[69]	India	monsoon	n/a	Hostel	NV	470 subjects	27.2–31.0	29.9
[70]	China	hot-humid subtropical	Summer	dormitory buildings	NV	465 subjects	25.0–28.7	26.2
[71]	USA	hot-humid subtropical	Summer	Classrooms	HVAC	496 students	22.0–24.5	23.5
[72]	China	Cold semi-arid climates and Cold desert climates	Winter	Classrooms	HVAC e NV	1206 students	13.0–18.0	14.2
[73]	Nigeria	Tropical	n/a	primary school buildings	NV	330 children (7–12 years)	25.2–32.3	28.8

n/a = not available.

Munonye and Ji [73], in Nigeria, evaluated the thermal perception of children aged 7 to 12 years. According to the temperature range found, children showed tolerance to higher temperatures. The authors suggested that installing air conditioning in the primary schools studied was not necessary, as it can lead to unnecessary energy consumption. So, knowing the comfort temperature of an environment for a group of people is used to possibly consume less energy, as the environment is projected where the group feels comfortable (highlighting the importance of knowing the real number of dissatisfied), thus not using HVAC [68].

One of the methods proposed for built comfort zones is based on probit or normit statistical analysis [74]. The probit is an estimation model derived from the normal frequency distribution curve. This type of analysis is indicated for data sets composed of dichotomous dependent variables, that is, of the type that assume only two values, of the yes or no type, having or not having, comfortable or not comfortable. For thermal comfort studies, probit curves are built taking into account those dissatisfied with the environment, whether due to cold or heat. This method was used by Hwang et al. [34], Wu et al. [43], Broday and Xavier [28], Nicol and Humphreys [75] and Toe and Kubota [76].

3. Materials and Methods

3.1. Selection, Sizing and Characterization of the Sample

The location chosen for the research was the classrooms of Federal University of Technology-Paraná (UTFPR), located in Ponta Grossa, Southern Brazil. With winters between June and September, according to data from the "Paraná Technology and Environmental Monitoring System" [77], the city has a temperate oceanic climate, with long warm summers and partly cloudy weather whereas winters are short and mild with partly cloudy skies and throughout the year, there is rainfall with temperatures ranging from 10 °C to 28 °C, as shown in Figure 1:

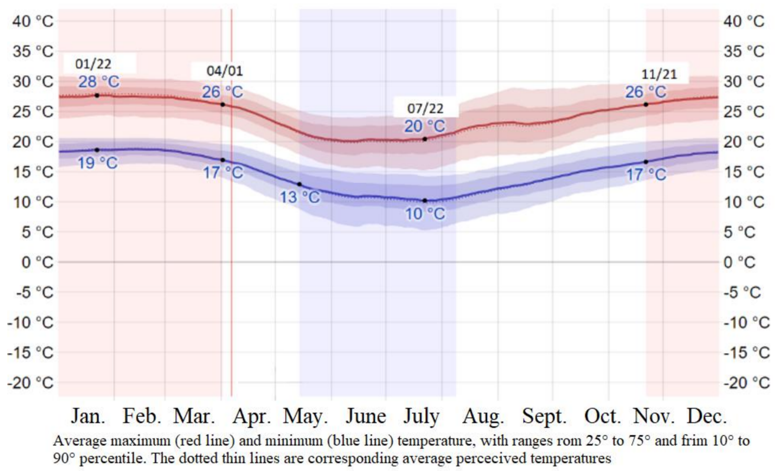

Figure 1. Maximum and minimum temperature averages.

The population defined for the research were students of undergraduate courses duly registered at UTFPR. With a sample of 481 students, who participated in 17 measurements in naturally ventilated classrooms, the research was conducted during the winter of 2019. During the research, no exclusion criteria were applied and the non-participation in the research was at the student's discretion.

There are six variables that act directly in determining thermal comfort according to the thermal balance model and that were collected for the development of this research, which are: environmental (air temperature, mean radiant temperature, relative humidity and air velocity) and personal effects (metabolic rate and clothing insulation). Environmental data, including air temperature, air velocity, globe temperature and relative humidity, were recorded by a Microclimatic Station at 1 min intervals. Figure 2 shows the equipment in detail.

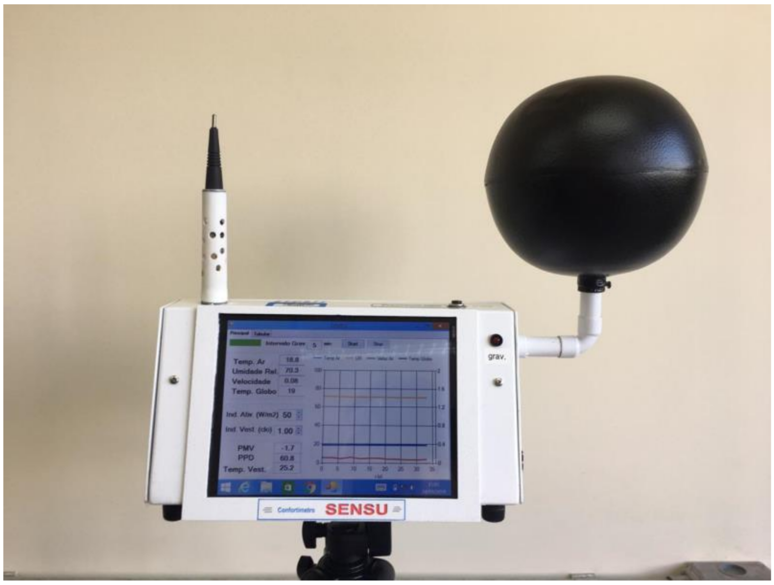

Figure 2. Microclimatic Station.

Personal variables were obtained as follows: the metabolic rate (M) was determined based on ISO 8996 [78] as 1.2 met, characteristic value for sedentary activities, typical of students. To collect the clothing insulation (clo), a questionnaire was applied, based on ISO 9920 [79], where the participant pointed out all the pieces of clothing he/she was wearing at the time of data collection. Through the questionnaire, it was also possible to collect the Thermal Sensation and Thermal Preference of the participants.

The variables of thermal comfort were used to determine the values of PMV and PPD. The Thermal sensation of each individual, in this research called AMV, as well as the Thermal preference, were used to determine the actual percentage of dissatisfied (APD) and consequently the thermal comfort zones. The questionnaire used in this research is available in Appendix A.

3.2. Experimental Measurement Design

Each data collection lasted 1 h per measurement in the classroom, with the researcher being able to collect data in more than one classroom per day. The total measurement time (1 h) was divided as follows: (a) Before starting the measurements, the device was assembled to achieve thermal equilibrium with the environment 20 min before the start of the collection of environmental variables. The device was assembled according to the recommendations of ISO 7726 [80] which deals with "Ergonomics of the thermal environment-Instruments for measuring physical quantities": 0.6 m from the ground due to the seated position in which the students are. (b) The measurement for collecting environmental variables was 40 min. After 20 min from the beginning of the measurement (half of the collection time), the questionnaires were applied to the students.

The Microclimatic Station was programmed to collect the aforementioned environmental variables every 1 min over the 40 min of collection, thus totaling 40 environmental readings per measurement. There was no direct intervention by the researcher during the surveys and any change in the environment, in order to regulate the local temperature, such as opening/closing windows, came from the participants themselves.

3.3. Comfort Temperature Analysis Using AMV

According to Yan, Wong and Jusuf [81] the temperature of comfort or thermal neutrality is generally determined by analyzing the relationship between the thermal sensation (AMV) and the operative temperature (T_{op}). Kazkaz and Pavelek [82] define operative temperature as the "uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat for radiation and convection as in the current non-uniform environment". To obtain the comfort temperature through the real thermal sensation, the linear regression model between the AMV and the operative temperature (T_{op}) was performed in this work.

3.4. Methodology for Predicting the Actual Percentage of Dissatisfied (APD)

The prediction of the actual percentage of dissatisfied (APD) in each measurement was calculated, taking into account the seven-point scale of the thermal sensation of [12] according to three different methods as detailed in Table 4:

Table 4. Methods for calculating each APD.

Reference	APD Nomenclature	Satisfaction Vote	Dissatisfaction Vote
[31]	APD_1	0	−3, −2, −1, +1, +2, +3
Category B ISO 7730 [12]	APD_2	−1, 0, +1	−3, −2, +2, +3
Proposed in this research by using ISO 10551 [83]	APD_3	−1 and +1 (considering vote 0 on the thermal preference scale) and 0	−1 and +1 (considering vote other than 0 on the thermal preference scale); −3, −2, +2 and +3

After obtaining the verified percentage of dissatisfied people according to the three perspectives presented, a non-linear adjustment was performed, similar to the PMV/PPD model, for the prediction of dissatisfied people, according to Equation (1):

$$\mathrm{APD} = 100 - \mathrm{a} \times \exp\left(-\mathrm{b}(\mathrm{AMV})^4 - \mathrm{c}(\mathrm{AMV})^2\right) \quad (1)$$

where:

APD = Actual Percentage of Dissatisfied.

AMV = Actual Mean Vote.

"a", "b" and "c" = Adjustment coefficients.

It is verified, through Equation (1), that the non-linear adjustment provides the amount of actual percentage of dissatisfied (APD) in the thermal environment for each AMV value entered.

3.5. Thermal Comfort Zones Proposition

For the proposition of thermal comfort zones, the statistical model, probit, was used. The probit is an estimation model derived from the normal frequency distribution curve. It is the most appropriate for analysis of dichotomous variables, that is, that assume only two values [84].

The probit curves of this research were built taking into account the thermal dissatisfaction with the environment due to being cold or hot. For this, a cutoff line was determined according to category B of ISO 7730: $-0.5 < \mathrm{PMV} < +0.5$. Thus, when replacing the value of AMV = 0.5 (category B, ISO 7730) in the equation of each APD, derived from Equation (1), its cutoff value was determined. If the percentage of dissatisfied with heat or cold was greater than or equal to the value found, the number 1 was assigned to the dichotomous variable; if the percentage was lower, the digit 0 was assigned to the dichotomous variable. For each of the three situations it was possible to construct two curves: a curve that represents those dissatisfied with the environment by cold (here graphically represented by the color blue) and another curve that represents those dissatisfied with the environment by hot (here represented graphically by the color red). In both cases, for the construction of the graph, the variable related to the APD was the operative temperature (T_{op}).

4. Results

4.1. Preliminary Results

A total of 481 questionnaires were filled by the students. The total sample of students who participated in the survey is shown in Table 5.

Table 5. Descriptive statistics of the sample.

Male: 346 Female: 135	Mean	Standard Deviation	Minimum	Maximum
Age	22.03	2.86	17	32
Height (cm)	174.05	8.64	152	196
Body mass (Kg)	74.24	15.29	42	130

Table 6 shows in detail the mean values of variables collected: Air temperature (T_{ar}), mean radiant temperature (T_{rm}), operative temperature (T_{op}), Air velocity (V_{ar}), Relative humidity (RH), Metabolic rate (M) and clothing insulation (I_{cl}), as well as the values of AMV, PMV, PPD, APD (1, 2 and 3) per measurement.

Table 6. Measurement results.

											APD		
	T_{ar} (°C)	T_{rm} (°C)	T_{op} (°C)	v_{ar} (m/s)	RH (%)	M (met)	I_{cl} (clo)	AMV	PMV	PPD	APD_1	APD_2	APD_3
1	19.73	20.12	19.93	0.03	61.91	1.2	0.77	−0.2	−0.7	15%	29.41%	11.76%	23.53%
2	20.41	20.48	20.45	0.04	61.41	1.2	0.9	−0.5	−0.3	7%	45.83%	4.17%	37.50%
3	21.71	21.64	21.68	0.04	69.44	1.2	0.72	0.8	−0.3	7%	73.33%	13.33%	53.33%
4	23.98	24.14	24.06	0.06	57.47	1.2	0.55	0.76	−0.1	5%	60.61%	18.18%	39.39%
5	17.77	17.81	17.79	0.03	64.01	1.2	0.98	−0.9	−0.8	18%	46.67%	20.00%	46.67%
6	28.26	27.67	27.97	0.15	40.03	1.2	0.38	1.75	0.41	9%	93.75%	62.50%	93.75%
7	27.52	26.89	27.21	0.12	37.55	1.2	0.38	1.46	0.27	7%	100.00%	38.46%	84.62%
8	19.44	19.13	19.29	0.03	66.79	1.2	0.89	−0.3	−0.6	12%	52.63%	2.63%	34.21%
9	19.12	19.12	19.12	0.03	59.62	1.2	0.96	−0.3	−0.5	11%	59.62%	7.69%	42.31%
10	17.95	17.69	17.82	0.04	66.76	1.2	0.9	−0.7	−0.9	23%	58.82%	11.76%	52.94%
11	20.66	20.52	20.59	0.08	65.75	1.2	0.73	0.12	−0.6	12%	58.82%	0.00%	41.18%
12	20.64	21.14	20.89	0.06	61.63	1.2	0.75	0	−0.5	10%	36.36%	0.00%	25.00%
13	18.47	18.38	18.43	0.07	68.13	1.2	0.84	−0.3	−0.9	22%	56.41%	7.69%	43.69%
14	19.89	19.81	19.85	0.04	60.34	1.2	1	−0.1	−0.3	7%	27.27%	3.03%	24.24%
15	23.29	23.17	23.23	0.08	60.15	1.2	0.51	0.5	−0.4	8%	58.33%	0.00%	58.33%
16	22.73	23.01	22.87	0.06	62.06	1.2	0.67	0.51	−0.1	5%	48.65%	2.70%	40.54%
17	21.21	21.21	21.21	0.03	61.39	1.2	0.78	0.03	−0.3	7%	33.33%	3.33%	26.67%

Note that the "M" values are fixed for all 17 measurements, as these are tabulated values for sedentary activities. The values of I_{cl} and AMV were obtained through the applied questionnaire, whereas the values of PMV, PPD and APD (1,2 and 3) were calculated. Figure 3 shows the comparison between the AMV values obtained from questionnaires and the PMV values, calculated from the data.

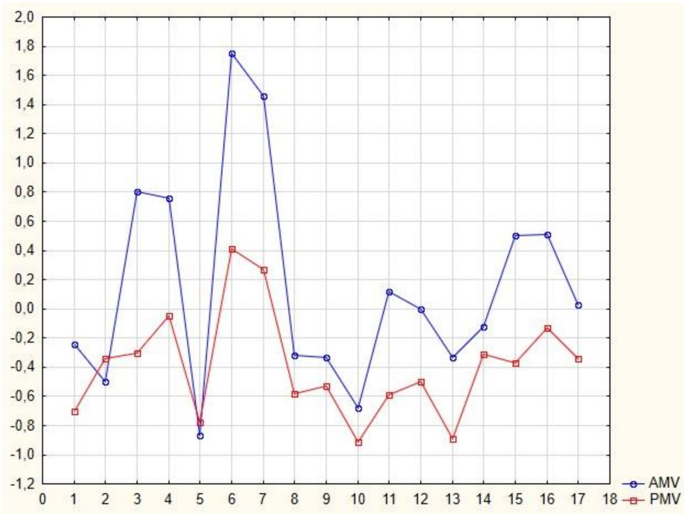

Figure 3. Comparison between AMV and PMV.

It was noticed that in 15 of the 17 measurements the PMV underestimates the real value of AMV, only in two measurements does the opposite occur. Therefore, for this research, it can be verified that in general, the PMV underestimated the real thermal sensation votes reported by the participants. This behavior was also repeated in the surveys [56,85,86] performed in hospitals [87], in mosques and [88] in classrooms.

4.2. Comfort Temperature (Neutral T_{op}) Analysis Using AMV

Through the linear regression analysis between T_{op} and AMV it was possible to determine the relationship between these variables. Figure 4 shows graphically the equation generated, with the error bars, as well as the R^2.

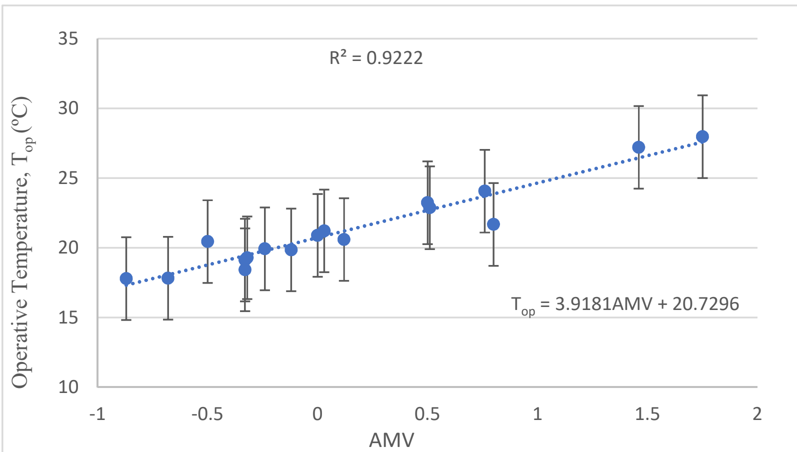

Figure 4. Linear relation between T_{op} and AMV.

Equation (2) represents the linear regression obtained:

$$T_{op} = 3.9181AMV + 20.7296 \quad (2)$$

To generate the TCZ through the regression analysis between T_{op} and AMV, it was necessary to replace the value of −0.5 and 0.5 (which correspond to the AMV values for category B of ISO 7730). This generated a TCZ of 18.77 °C–22.69 °C with a range of 3.92 °C. Table 7 summarizes other studies that also related AMV to T_{op}. It is worth mentioning that some authors, instead of using the term "Actual Mean Vote" (AMV), used the term "thermal sensation vote" (TSV), these being equivalent terminologies.

Table 7. Relationship between T_{op} and AMV.

Reference	Equation	Neutral T_{op} (°C)	Type of Environment
[28]	$AMV = 1.4316T_{op} - 30.62$	21.39	Offices
[46]	$TSV = 0.0448T_{op} - 0.9628$	21.5	Classrooms
[88]	$TSV = 0.26T_{op} - 5.68$	21.84	Classrooms
[89]	$AMV = 0.1334T_{op} - 3.48$	26.08	Mosques
[90]	$TSV = 0.491T_{op} - 13.1$	26.68	Offices
This research	$AMV = 0.2354T_{op} - 4.8675$	20.73	Classrooms

In general, this study found the lowest neutral operative temperature among the aforementioned studies, through the linear relationship between T_{op} and AMV. For comparison, for all studies carried out in classrooms, these were naturally ventilated environments. Zhang et al. [46] conducted their study at a Chinese university with an adult audience, just as in this work. The study performed by Teli, Jentsch and James [88] also generated an equation closer to the one presented here, despite being carried out with children between 7 and 11 years old in England during summer. The authors used an approach based on the building's construction guidelines to verify its impact on the feeling of comfort.

4.3. Determination of APD Curves

Figure 5 shows a comparative graphic between the values of the calculated PPD and the APDs resulting from the application of the questionnaire in the 17 measurements performed in the field:

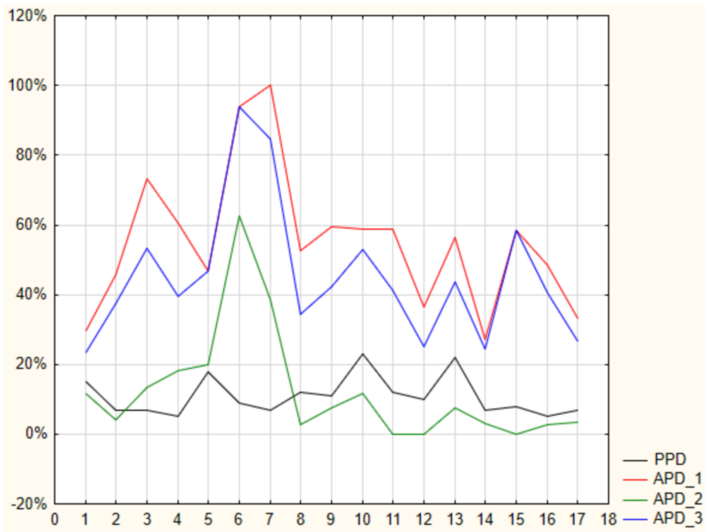

Figure 5. Comparison between the values of APDs and PPD.

It is noted that the values of APD_1 are almost always higher than the others. This behavior was already expected since method 1 is the most rigid and considers only those people to be satisfied who voted 0 on the thermal sensation scale. Following this line of thought, the behavior of the APD_2 index value was, as expected, always the lowest among APDs, since it has the most "relaxed" perspective among them. APD_3 has always remained intermediary, but tending to be closer to APD_1, even reaching values. From these values, it was possible to determine the curves for each APD in comparison to the AMV value based on the original PPD curve. Figure 6 shows the curve for APD_1.

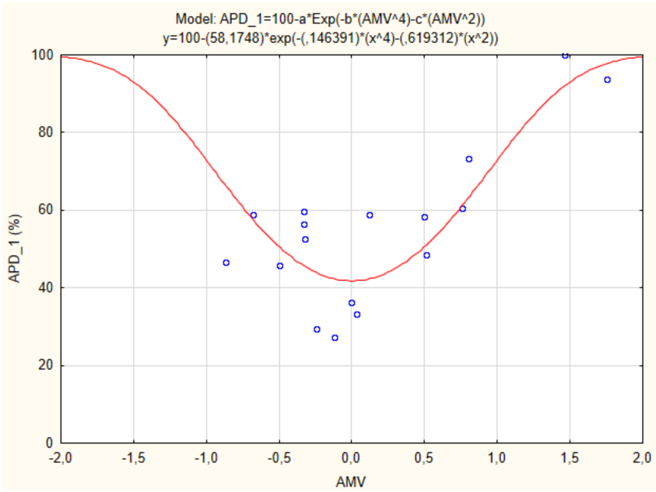

Figure 6. APD_1.

The curve generated in Figure 6 is expressed by Equation (3):

$$APD\_1 = 100 - (58.1748) \times \exp((-0.146391 \times AMV^4) - (0.619312 \times AMV^2)) \quad (3)$$

The minimum value of this curve (AMV = 0) was 41.83%.

Figure 7 shows the curve for APD_2.

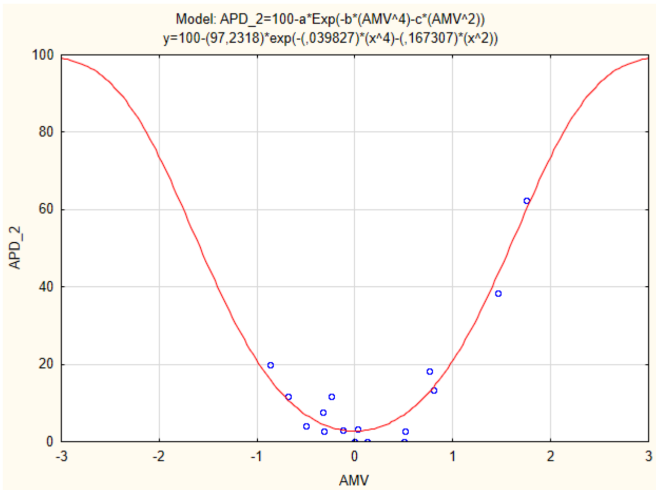

Figure 7. APD_2.

The curve generated in Figure 7 is expressed by Equation (4):

$$APD\_2 = 100 - (97.2318) \times \exp((-0.039827 \times AMV^4) - (0.167307 \times AMV^2)) \quad (4)$$

This curve adopts the perspective of ISO 7730 [12] and resulted in a minimum value of dissatisfied of 2.77%, lower than the standard (5%).

Figure 8 illustrates the curve for APD_3.

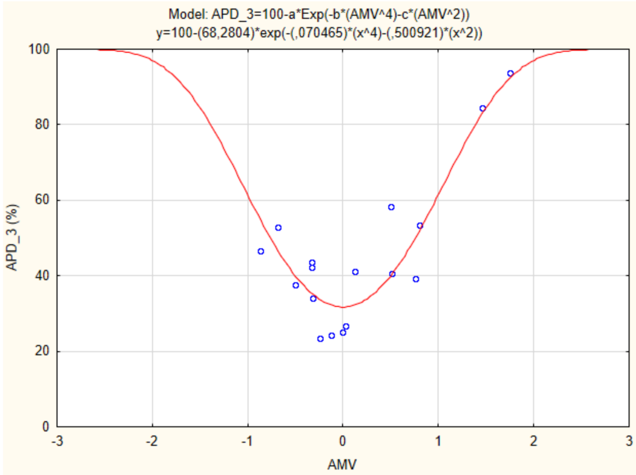

Figure 8. APD_3.

The curve generated in Figure 8 is expressed by Equation (5):

$$APD\_3 = 100 - (68.2804) \times \exp\left(\left(-0.070465 \times AMV^4\right) - \left(0.500921 \times AMV^2\right)\right) \quad (5)$$

As a result of the methodology suggested in this research, the equation determined a minimum value of 31.72% of dissatisfied for this environment, being this an intermediate value between APD_1 and APD_2. In summary, Table 8 shows the values of R^2, minimum APD (APD_{min}) having AMV = 0, and the APD value corresponding to category B of ISO 7730 corresponding to the value of AMV = 0.5 replaced in each APD equation.

Table 8. Equations APD.

Nomenclature	Equation	R^2	APD_{min}	AMV = 0.5
APD_1	$100 - (58.1748) \times \exp\left(\left(-0.146391 \times AMV^4\right) - \left(0.619312 \times AMV^2\right)\right)$	0.844	41.83%	50.62%
APD_2	$100 - (97.2318) \times \exp\left(\left(-0.039827 \times AMV^4\right) - \left(0.167307 \times AMV^2\right)\right)$	0.969	2.77%	6.98%
APD_3	$100 - (68.2804) \times \exp\left(\left(-0.070465 \times AMV^4\right) - \left(0.500921 \times AMV^2\right)\right)$	0.914	31.72%	40.02%

Figure 9 shows a comparison between the 3 APD curves and the original PPD curve.

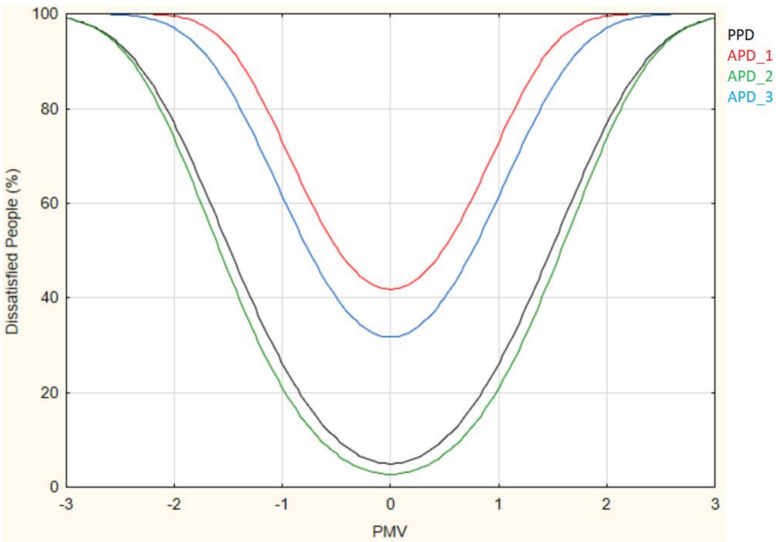

Figure 9. Comparison between APDs and PPD.

APD_1 recorded the highest minimum percentage of dissatisfied people. This behavior was expected due to the strong rigor of its methodology. Normally, surveys that present this rigor of considering satisfied only the participant who votes 0 on the 7-point scale of thermal sensation have a high APD, as observed in: [28,31], with APD_{min} values of 47.5% and 52.31% respectively, values close to those found in this research. In relation to APD_2, which follows the perspective of ISO 7730 [12], the value of 2.77% was lower than the 5% established by the standard. APD_3 remained intermediate between both and tending to the value of APD_1.

4.4. Construction of Thermal Comfort Zones

Table 9 shows the construction of the dichotomous variables (1 and 0) for the APDs taking into account the number of dissatisfied people by hot or cold.

The cutoff used symbolizes the percentage of dissatisfied according to category B of ISO 7730. For APD_1 if the percentage of dissatisfaction was greater than or equal to 50.62%, the value 1 was assigned, if the value was less than 50.62% the value 0 was assigned. The same pattern was followed for APD_2 and APD_3 with cuts of 6.987% and 40.02%, respectively.

With the values of the dichotomous variables, the graphs that represent the Probit model for each APD in relation to the operative temperature (T_{op}) were constructed. The blue line of the graphs represents the dissatisfied with the cold, while the red line symbolizes the dissatisfied with the heat. An additional green line was added with the cutoff value. The point of intersection between the blue and red lines is considered the point of neutral Operative Temperature (T_{op}) where there is the least amount of dissatisfied with cold and heat at the same time. The intersection between the green line and the blue and red lines represents the thermal comfort zone obtained from the specific APD. Figure 10 shows the result for APD_1.

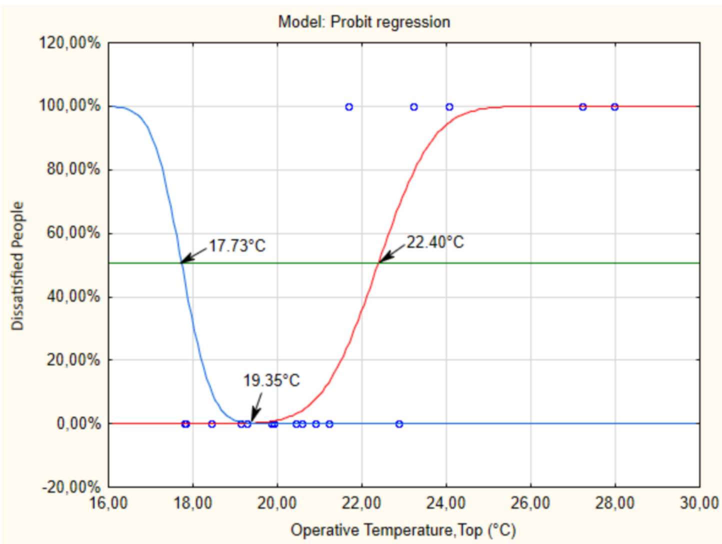

Figure 10. *Probit* APD_1.

Table 9. *Probit* Model.

APD_1		Cutoff Line 50.62%		APD_2		Cutoff Line 6.98%		APD_3		Cutoff Line 40.02%	
Dissatisfied by Hot	Dissatisfied by Cold	Hot	Cold	Dissatisfied by Hot	Dissatisfied by Cold	Hot	Cold	Dissatisfied by Hot	Dissatisfied by Cold	Hot	Cold
11.76%	17.65%	0	0	0.00%	11.76%	0	1	5.88%	11.76%	0	0
0.00%	45.83%	0	0	0.00%	4.17%	0	0	0.00%	25.00%	0	0
66.67%	6.67%	1	0	13.33%	0.00%	1	0	40.00%	0.00%	0	0
57.58%	3.03%	1	0	18.18%	0.00%	1	0	33.33%	0.00%	0	0
0.00%	46.67%	0	0	0.00%	20.00%	0	1	0.00%	40.00%	0	0
93.75%	0.00%	1	0	62.50%	0.00%	1	0	87.50%	0.00%	1	0
100.00%	0.00%	1	0	38.46%	0.00%	1	0	61.54%	0.00%	1	0
13.16%	39.47%	0	0	0.00%	2.63%	0	0	5.26%	18.42%	0	0
17.31%	42.31%	0	0	0.00%	7.69%	0	1	3.85%	25.00%	0	0
2.94%	55.88%	0	1	0.00%	11.76%	0	1	2.94%	41.18%	0	1
35.29%	23.53%	0	0	0.00%	0.00%	0	0	11.76%	11.76%	0	0
18.18%	18.18%	0	0	0.00%	0.00%	0	0	6.82%	6.82%	0	0
15.38%	41.03%	0	0	0.00%	7.69%	0	1	10.26%	28.21%	0	0
9.09%	18.18%	0	0	0.00%	3.03%	0	0	3.03%	18.18%	0	0
54.17%	4.17%	1	0	0.00%	0.00%	0	0	33.33%	4.17%	0	0
48.65%	0.00%	0	0	2.70%	0.00%	0	0	27.03%	0.00%	0	0
16.67%	16.67%	0	0	3.33%	0.00%	0	0	6.67%	10.00%	0	0

Considering 50.62% as a cutoff, the probit model generated, for APD_1, a thermal comfort zone varying between 17.73 °C and 22.40 °C, with a neutral operative temperature of 19.35 °C, where theoretically, only 0.18% of people would be dissatisfied. Figure 11 details the probit model generated for APD_2.

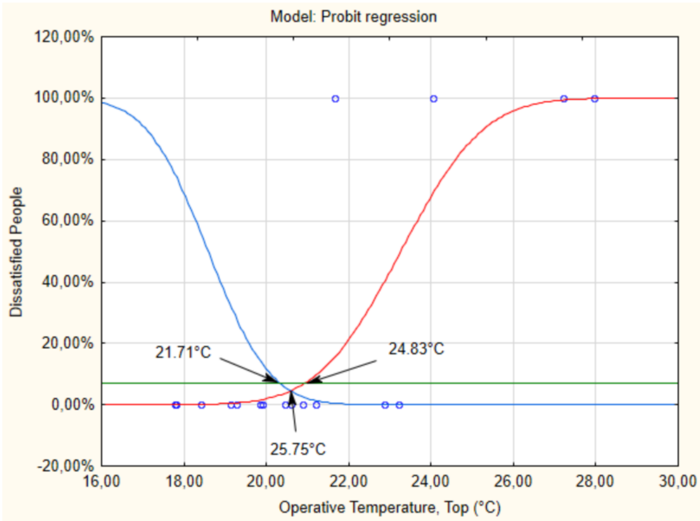

Figure 11. Probit APD_2.

According to the suggested cutoff of 6.98%, the thermal comfort zone is 20.71 °C to 20.93 °C with a neutral operative temperature of 20.75 °C, where 5.28% of people would be dissatisfied. Figure 12 shows the model's result for APD_3.

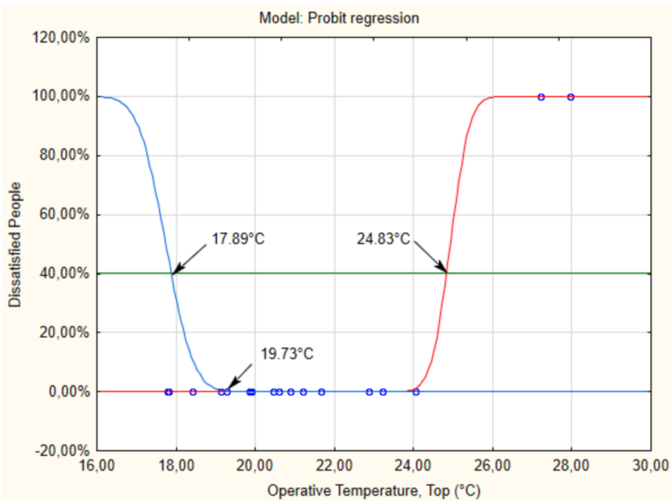

Figure 12. Probit APD_3.

With a cutoff equal to 40.02%, the comfort zone for APD_3 varies from 17.89 °C to 24.83 °C, with a neutral operative temperature of 19.73 °C, being approximately 0.03% of dissatisfied. Table 10 summarizes the values for neutral operative temperature, thermal comfort zone and the range obtained from each TCZ.

Table 10. Neutral Top and TCZs.

Nomenclature	Neutral T_{op}	TCZ	Range
APD_1	19.35 °C	17.73 °C–22.4 °C	4.67 °C
APD_2	20.75 °C	20.71 °C–20.93 °C	0.22 °C
APD_3	19.73 °C	17.89 °C–24.83 °C	6.94 °C

The three APDs brought neutral Operative Temperatures relatively close. The considerable difference was in relation to the TCZ generated by APD_2 with very close values and a range less than 1 °C. This behavior can be explained by the fact that the percentage of dissatisfied for APD_2 is by far the lowest among the three (6.98%). The TCZ obtained through APD_3 was the highest among them, with a range of 6.94 °C, followed by the TCZ relative to APD_1 with a range of 4.67 °C. It is interesting to note that even admitting a lower percentage of dissatisfied people, APD_3 generated a wider TCZ than APD_1.

5. Discussions and Conclusions

In relation to the thermal comfort zone suggested by ASHRAE [13] from 23 to 26 °C for winter, all the TCZs calculated here have lower minimum and maximum values, tending to colder temperatures than those suggested by the standard. In addition, the zones generated by APD_1 and APD_2 have greater ranges. Hwang, Lin and Kuo [91] explain that any different level of existing thermal comfort is an opportunity to save energy consumption, either by greater ranges than the thermal comfort standards or preferred temperatures being cooler or hotter due to the adaptation of the sample to the respective climate. Table 11 shows studies developed during the winter and their respective TCZ for comparison with the TCZ generated by the perspective suggested in this research (APD_3).

Table 11. TCZ developed for winter in other studies.

Reference	TCZ (°C)	Neutral T_{op} (°C)	Range
[92]	13–18	14.2	5
[28]	19.61–22.61	21.1	3
[47]	20.2–23.6	21.4	3.4
[68]	19.5–21.8	20.6	2.3
This research	17.89–24.83	19.73	6.94

The work of Jiang et al. [92], carried out on primary and secondary school students in China, generated the TCZ with colder temperatures among the research, reaching the minimum value of 13 °C and maximum of 18 °C, as well as the lowest neutral T_{op}. Regarding the TCZ range, the largest was generated in this research, followed by the research of Jiang et al. [92].

All TCZs presented in Table 11 have lower temperatures than those suggested for winter by ASHRAE (2017) of 23–26 °C and, except for that proposed by Liu et al. [68]. This shows the importance of verifying the values derived from the particular characteristics of each region when determining a thermal comfort zone, in order to potentiate the relationship between thermal comfort and minimum energy consumption.

The results showed that the PMV mostly underestimates the votes of the actual mean vote (AMV), collected in field studies. Therefore, the index proposed by Fanger is not an ideal predictor to be applied under the conditions suggested by this research. The neutral operative temperature based on the thermal sensation votes was 20.73 °C. The temperature was much lower than the 24.5 °C proposed by ASHRAE for the winter, under the conditions proposed by this study.

This research adopted three methods to determine the actual percentage of dissatisfied. The one based on the work of Araújo and Araújo [31], was the most rigid and generated a percentage of dissatisfied called APD_1. The second perspective adopted here was based on the standards adopted by ISO 7730 and generated a percentage of dissatisfied called APD_2. The third method was proposed in this research, using the thermal preference scale found in ISO 10551 (1995), which generated the percentage APD_3. Based on ISO 7730 category B, the percentage of dissatisfied people were: 50.62% (APD_1); 6.98% (APD_2); and 40.02% (APD_3).

The TCZ calculated from APD_1, APD_2 and APD_3, using the probit method, are respectively: 17.73 °C–22.4 °C; 20.71 °C–20.93 °C and 17.89 °C–24.83 °C. All the percentages adopted here led to thermal comfort zones that are potentially economical in terms of energy, due to having colder temperature values than that adopted by the ASHRAE (2017) standard for winter. In addition, the TCZs generated by the use of APD_1 and APD_3 have a greater range than that of the previously mentioned standard. It is concluded that the use of TCZ, created based on the actual percentage of dissatisfied, is a promising strategy to maintain comfort and maximize energy savings.

Based on the findings of this research, opportunities are suggested that can be developed in future studies, such as: other methods for determining thermally dissatisfied people, generating other thermal comfort zones and the adoption of the adaptive thermal comfort models, considering the adaptive behaviors of the participants.

6. Study Limitations

Thermal comfort, the general theme of this research, fits within the spectrum of ergonomics, as it is a multidisciplinary study whose main objective is to provide an environment in which people are not negatively affected by the thermal environment and can carry out their activities in a satisfactory way. The term environmental assessment is classified according to the type of environment. In the case of moderate environments, the following stand out: the PMV and PPD indices, which currently have the ISO 7730 standard application procedure based on Fanger studies. This research was carried out based on the Fanger model and adaptive thermal comfort models were not used.

As the sensation of thermal comfort of each individual goes far beyond the physiological response of its organism to environmental parameters, factors such as emotional state, perseverance and time of day might influence the sensation of thermal discomfort. However, these factors were not taken into account when carrying out the study and this research was limited to working on the general theme of thermal comfort, specifically with the PPD index and its application to determine thermal comfort zones. Also, people's subjective response was considered in this research through direct answers, using the scale provided in ISO 7730. Peoples' interpretations of scales may change with contextual factors, such as climate, language and season [93].

Chong et al. [42] show that wide thermal comfort zones guarantee a reduction in energy consumption, but the purpose of this work was just to demonstrate them, since the research was carried out during the winter and the classrooms did not have heating systems, making it impossible to calculate the energy saving. The methodology used here can be replicated in indoor environments under similar conditions, guaranteeing the extrapolation of data. In this study, due to the pandemic of the new coronavirus (SARS-CoV-2), the sample was reduced, making it impossible to collect new data in the year 2020. Thus, the results from new studies might be different from those presented here, when a larger sample is used.

Author Contributions: Conceptualization, P.F.d.C.P. and E.E.B.; methodology, E.E.B.; software; formal analysis, P.F.d.C.P. and E.E.B.; investigation, P.F.d.C.P.; writing—original draft preparation, P.F.d.C.P.; writing—review and editing, E.E.B.; supervision, E.E.B.; project administration, E.E.B.; funding acquisition, P.F.d.C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CAPES, grant number 001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

AMV	Actual Mean Vote
APD	Actual Percentage of Dissatisfied
HVAC	Heating, Ventilation and Air-Conditioning
IEQ	Indoor Environmental Quality
MTS	Mean Thermal Sensation
MTS	Mean Thermal Sensation Vote
PMV	Predicted Mean Vote
PPD/PD/PDacc	Predicted Percentage of Dissatisfied
TCZ	Thermal Comfort Zones
T_o/T_{op}	Operative Temperature
TSV	Thermal Sensation Vote

Appendix A. Thermal Comfort Questionnaire

Age: _____ Height:_____ Weight: _____ Gender: _____

(1) Mark the clothes you are wearing (Adapted from ISO 9920/2007):

Underwear	**Pants**	**T-shirts, Sweaters and Coats**	**Accessories**
Leotard	Shorts	Sleeveless waistcoat	Shoes with leather soles
Knickers	Pants fine material	Fine T-shirt	Shoes with rubber soles
Bra	Jeans	Thick T-shirt	Sneakers
Underpants	Farming pants	Coat	Boots
Shirts, Blouses	**Dresses and Skirts**	Thick jumper	Fine sweater
Short-sleeved shirt	Short skirt	Fine blazer	Ankle socksBoots
Long-sleeved shirt fine material	Long skirt	Thick blazer	Knee-length socks
Normal long-sleeved shirt	Short-sleeved dress	T-shirt	GlovesBoots
Flannel shirt	Long-sleeved dress		Tights
Fine, light blouse, long sleeves	Normal dress		Tie/Ribbon

(2) Considering your thermal sensation, how are you feeling? (ISO 7730/2005)

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
−1	Slightly cool
−2	Cool
−3	Cold

(3) Considering your thermal preference, how would you like to be feeling? (ISO 10551/1995)

+3	Much warmer
+2	Warmer
+1	A little warmer
0	Neither warmer nor cooler
−1	Slightly cooler
−2	Cooler
−3	Much cooler

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