PET Comfort Index Calibration Using Decision Trees

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1. Introduction

Thermal sensation derives from the interaction of environmental and individual variables, requiring the use of an index that should incorporate them. However, acclimatisation to different weather conditions calls upon calibration of the thermal comfort index employed before its application as a tool for evaluating thermal conditions in urban areas. The current research, developed in the tropical city of Salvador, is part of an inter-institutional umbrella project, Urban Climate, Urban Design and Global Climate Changes (ASSIS; NERY; KATZSCHNER, 2007) aimed at developing a methodology to calibrate such a thermal index by applying it to different cities and climates.

The human body perceives a range of physiological cold and heat stress, with the Neutral condition theoretically associated with thermal comfort perception, in which a person would prefer neither warmer nor cooler surroundings (FANGER, 1970). ISO 7730 defines Comfortable or Neutral condition by those environmental conditions, which enable the human body to be in thermal balance, i.e., "the internal heat production in the body is equal to the loss of heat to the environment" (INTERNATIONAL ..., 2005). The thermal balance equation is a function of heat exchange by radiation, convection, conduction and evaporation processes. Environmental factors of air temperature, mean radiant temperature, air pressure and air speed in addition to individual variables, such as age, gender, weight, height, activity and clothing, influence heat transfer processes.

A large number of thermal indices have been set up to estimate the thermal state of man and foremost to satisfy man's desire to feel comfortable (FANGER, 1970). Many of these indices did not consider all variables of thermal comfort, much less in an integrated manner, emphasizing quantitative results over subjective ones. In the 1970s, Fanger (1970) proposed the Predicted Mean Vote (PMV) index based on the underlying idea of combining the physical and subjective factors that create thermal comfort. PMV was adopted by ISO 7730 (INTERNATIONAL ..., 2005) and other standards and we applied Fanger´s seven-point scale to obtain the thermal response of pedestrians in the present research.

Similarly to PMV, the thermal comfort index Physiological Equivalent Temperature (PET) (°C), also applied in this research, is based on energy balance and integrates environmental and individual variables. PET was proposed by Höppe and Mayer in 1987 (HÖPPE, 1993; 1999) and is expressed in a widely known unit (°C). Matzarakis and Amelung (2008) detailed the calculation of PET index (°C) and Höppe (1993; 1999) systematised the PET model into algorithms for computer applications.

The complexity of variables that arise from the interaction of differentiated weather conditions, human physiology and perception requires the use of multivariate data analysis for interpreting field research results. Decision Tree (DT) technique, used in this study provide a clear representation of relationships in a dataset.

Tree models provide an alternative to regression and classification problems. Successive divisions of data adjust the models to get increasingly homogeneous subsets, according to their values, to create a hierarchical classification based on statements of the "then" logical operator. They result in a hierarchical DT rules ranked to predict or classify. The algorithm used to divide the data in the DT models seeks to find the most important independent variables, namely, those that provide the maximum segregation data (WESTPHAL; BLAXTON, 1998).

Decision Tree analysis allowed relating thermal perception to PET Index (°C), a necessary condition to calibrate the latter for population acclimatised to the climatic conditions encountered in the tropical city of Salvador, Brazil.

2. The abstract

This study is part of an inter-institutional umbrella project, Urban Climate, Urban Design and Global Climate Changes that aimed at analysing the response of the thermal comfort index, Physiological Equivalent Temperature (PET) (°C), for acclimatised residents in the tropical city of Salvador, Brazil, by

associating PET (°C) intervals with voted thermal perception. PET defines its neutral condition based on equalized human heat balance. However, as people are adapted to different climatic conditions, classes of thermal perception, including the comfort zone will differ according to the local climate. The methodology used involved carrying out meteorological measurements of air temperature and humidity, solar radiation, wind velocity and simultaneously interviewing acclimatised pedestrians about their thermal perception. The population sample included those residents living in Salvador for more than a year, between 20 and 59 years old. The research was carried out in open urban spaces. In total 1,435 interviews were conducted. Decision Tree - DT technique of exploratory data analysis was used to calibrate the PET index (°C). The variable used was Fanger's seven-point scale categories: +3 (Hot); +2 (Warm); +1 (Slightly Warm); 0 (Comfortable); -1 (Slightly Cool); -2 (Cool) and -3 (Cold). Through statistical analysis, using DT and considering 50% of the responses, only the "Hot" category showed a value above that (51.5%). 50% criterion was considered insufficient to distinguish the seven categories of thermal perception, and we adopted the criterion of 30% of responses. For the latter criterion results were: "Hot" (category 1) PET index more than 34.1 °C; "Warm" (category 2) PET index is between 29.4 to 34.1 °C; "Slightly Warm" (category 3) PET index is between 26.8 to 29.4 ºC; "Comfortable" (category 4), obtaining the upper limit for the PET index inferior to 26.8 ºC, whereas the lower limit of comfort could not be established.There were no responses for "Cool" and "Cold" even in winter. To conclude, the study proposes PET index ≤ 26.8 °C as the upper limit for the category, "Comfortable" for the city of Salvador.

3. Materials and Method

In general, the applied methodology consisted of measuring environmental variables in urban open spaces in Salvador, Brazil, and simultaneously interviewing the population regarding their thermal perception and obtaining individual variables. Afterwards, we calculated PET (°C) thermal comfort index, followed by statistical analyses through the Classification and Regression Tree (CART) algorithm (SPSS 17.0), which related thermal perception to the measured variables. More details are in Andrade et al. (2004), Katzschner (2011), Fé et al. (2007) and Souza (2010).

The research team conducted the field research in 2 consecutive days in each of the four seasons, from 2009 to 2010. Measurements occurred at 10 minute-intervals from 2:00 to 5:00 PM, and the environmental variables measured were: Temperature (T_a) (° C), Relative Humidity (UR) (%), Wind Speed (V) (m / s) and Globe Temperature (T_g) (° C). Two meteorological stations (WID600 and FS40H) registered the first two variables, whereas two anemometers (Minipa, MDA11 model) measured air speed. Two 0.04m grey globe thermometers, connected to the temperature sensor (Farnell Newark, code 41K4848), measured Tg (°C). Both stations and the globe thermometers were fixed on a tripod at a height of 1.5m above ground and the anemometers at 2.0m to avoid nearby obstacle influences. The mean radiant temperature (MRT) (°C) was calculated from the data by applying the equation for forced convection (ISO 7726, INTERNATIONAL ..., 1998). Simultaneously, we applied questionnaires to pedestrians to determine their thermal perception through the PMV seven-point scale, namely, "Cold" (-3), Cool (-2), "Slightly Cool" (-1), Neutral (0), "Slightly Warm" (1), "Warm" (2) and "Hot" (3) (ISO 7730, INTERNATIONAL ..., 2005).

The researchers interviewed a statistically representative sample of the city's population and collected the individual variables, Weight (kg), Height (m), Age, Gender, Metabolic Activity (W) and Clothing (Clo). Respondents were residents of Salvador for a year or more, with age ranging between 20 and 59 years, which corresponds to a standard age interval (IBGE, 2000) for counting the population. Applying the equations 01 and 02 (BARBETTA, 1994) for this universe, i. e., N = 1,355,806 inhabitants, and adopting a sampling error E_o = 3%, the sample size n = 1,110, and n_o, a first approximation of the sample size,

$$n = N.n_o / N + n_o \qquad [Eq.01]$$
$$n_o = 1/E_o^2 \qquad [Eq.02]$$

Furthermore, interviewees had to meet specific criteria, namely, they should usually work in a non-artificially conditioned environment, should spend more than 15 minutes outdoors, should not have ingested alcohol or cold, spicy or greasy food within an hour of the interview, and should be in good health, not in menopause or pregnant.

The PET thermal comfort index (°C) was obtained using the PET model systematized by Rayman® application, v. 1.2 (RUTZ; MATZARAKIS; MAYER, 2000) by inputting the individual variables of each subject (gender, age, approximate weight, height, activity, and clothing) and the environmental variables measured (air and mean radiant temperature, humidity and air speed) at the time of the thermal assessment opined by the respective interviewee. For each subject, we created a pair comprised of PET (°C) value and the thermal perception category of the seven-point scale.

For the purposes of the CART algorithm, the criterion for partition of the available data terminal nodes was established as equivalent to 50 individuals, with standard deviation 0.002. We adopted two variables for the calibration of PET (ºC): the dependent variable was reported by the thermal perception, a categorical variable with seven categories, and the independent variable was the PET Index (ºC), a continuous numeric variable.

To be sure, a decision tree can be defined as a direct acyclic graph that satisfies the following properties (SAFAVIAN and LANDGREBE, 1991): (1) the hierarchy is called a tree, and each segment is called node; (2) there is a node, called root, which contains the entire database; (3) this node contains data that can be subdivided into other sub-nodes, called child nodes; (4) there is only one path between the root node and each node; and (5) when the data node cannot be subdivided into another subset, it is considered a terminal or leaf node.

The algorithm adopted for sorting the data is a variant of the CART algorithm, which establishes a relationship between the independent and dependent variables. Successive binary divisions in the data set adjust the algorithm, in order to make the resulting subsets increasingly more homogeneous with respect to the dependent variable. A binary tree structure represents these divisions, where each node corresponds to a division (BREIMAN et al., 1984).

4. Results

The field research interviewed 1,435 individuals, obtaining 1,002 valid questionnaires, after removing atypical observations for not fulfilling the required criteria or incomplete information. Of the total respondents, 34% reported being in thermal comfort, 64% in positive thermal stress, which represents the sum of categories "Slightly Warm," "Warm" and "Hot", and just 2% reported negative thermal stress.

Figure 1 shows the Decision Tree (DT) with seven nodes, including four terminal ones. Each node represents the group of individuals formed of similar characteristics classified by data mining. The depth of the tree structure represents levels of classification aggregated by frequency of occurrence in the branches of the structure, which in this case, equalled to three layers.

In the first data partition (Figure 1), PET value equals 29.4 °C, sectioning the data into two main groups: (1) PET ≤ 29.4 °C; and (2) PET > 29.4 °C. Group 1 - Node 1, with smaller PET values, predominantly comprises individuals who reported “Comfortable” (category 4, with 41.4%). Group 2 - Node 2 and higher PET values consists mostly of individuals who reported heat stress (category 2, with 34.2%). Successive binary divisions further established PET values of the terminal nodes: Node 3 - PET values ≤ 26.8 °C; Node 4 - PET values from 26.8 to 29.4 °C; Node 5 - PET values from 29.4 to 34.1 °C; Node 6 - PET values ≥ 34.1 °C. For each interval, terminal node, DT (Figure 1) displays the frequencies of occurrence of each of the five relevant categories of thermal perception.

Table 1 shows the percentages of responses per PET interval defined by DT. The highest percentages of thermal perception responses allow associating the seven-point categories with PET intervals defined by DT. Hence, values of “Hot” thermal perception (category 1) correspond to PET index above 34.1 °C, and equivalent to 51.5% of interviewees, whereas “Warm” (category 2) accounts for PET values between 29.4 and 34.1 °C, and consistent with 36.2% of responses. “Slightly Warm” (category 3) reaches 21.9% of responses with PET below 26.8 °C. “Comfortable” (category 4) sets an upper limit of PET lower than 26.8 °C, corresponding to 48.8% of interviewees. “Slightly Cool” (category 5) achieves 3.5%, with PET below 26.8 °C.

5. Discussion

The Decision Tree technique searches values of the independent variable that increasingly promotes segregation of data. By adopting a minimum of 50% of responses, as a criterion to define PET intervals, “Hot” (category 1) is the only clearly determined category (51.5% of responses). However, adding two DT PET intervals (29.4<PET ≤ 34.1 ºC and PET≥34.1 ºC), “Warm” (category 2) could be created for PET above 29.4 ºC. Similarly, “Comfortable” (category 4) could be determined for PET < 29.4 ºC. Yet, “Slightly Warm” (category 3) and “Slightly Cool” (category 5) could not be distinguished at this level (Table 2).

As the adoption of minimum 50% response criterion was not satisfactory to distinguish the intervals of PET index per category, the researchers applied the minimum criterion of 30% of responses (Table 2) to analyse DT results. At this level, “Hot” remained with lower limit of 34.1 ºC and the subsequent intervals for “Warm” (category 2) and ”Comfortable” (category 4) became 29.4 to 34.1 ºC and ≤ 26.8 ºC, respectively. There was no clear definition of ”Slightly Warm” (category 3) range of PET values (26.8<PET≤ 29.4 ºC). Rather, this PET interval resulted by inference, as it could not be determined by the 30% criterion, but it sits between the more clearly defined ”Warm” and ”Comfortable” categories. For both 50% and 30% criteria, the lower limit of ”Comfortable” could not be found. A small number of

responses prevented determining the ”Slightly Cool” (category 5) range of PET. The DT technique indicates that with 30% criterion it is possible to derive PET intervals for calibration.

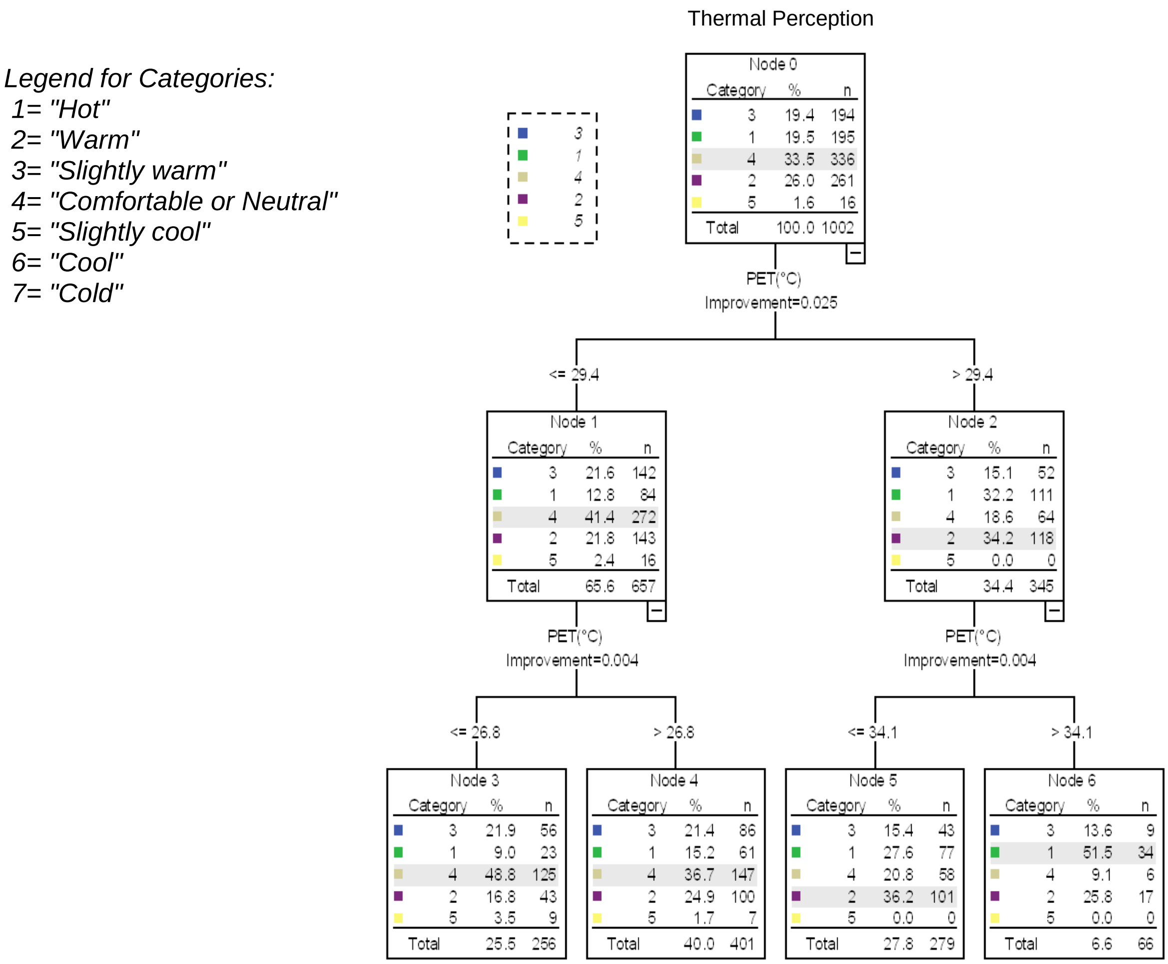

Fig.1 – Decision Tree (DT) and Classification for calibration of PET Index (°C). Source: Authors, using CART algorithm (SPSS 17.0).

Table 1 – DT results (%) in relation to PET (°C) intervals

PET (°C) ↓	Category → / Node ↓	1 Hot	2 Warm	3 Slightly Warm	4 Comfortable	5 Slightly Cool
				(%)		
≤ 26.8	**3**	9.0	16.8	21.9	48.8	3.5
26.8 - 29.4	**4**	15.2	24.9	21.4	36.7	1.7
29.4 - 34.1	**5**	27.6	36.2	15.4	20.8	0.0
≥ 34.1	**6**	51.5	25.8	13.6	9.1	0.0

Source: Authors.

Recall that the inter-institutional umbrella project in tropical and temperate climates applied the same methodology aiming at calibrating PET thermal index. Table 3 compares the results of calibrations in Germany, cities of Kassel and Freiburg (KATZSCHNER, 2011), China, Hong Kong, (KATZSCHNER, 2011), and Brazil, in Belo Horizonte (HIRASHIMA, 2010) and Salvador (Fé et al., 2007) and the present research. Table 4 compares the results from each calibration and shows PET intervals related to thermal perception, accordingly.

Table 2 – PET (°C) Index Calibration using DT

	Category	DT at 50%	DT at 30%
1	Hot	PET > 34.1 ºC	> 34.1 ºC
2	Warm	PET > 29.4 ºC	29.4<PET≤34.1 ºC
3	Slightly Warm	-	26.8<PET≤ 29.4 ºC
4	Comfortable	PET < 29.4 ºC	≤ 26.8 ºC
5	Slightly Cool	-	-

Source: Authors

The studies developed for temperate and subtropical climates (KATZSCHNER, 2011) established PET index intervals for thermal perception ranges from "Hot" to "Cold" determining all the seven-point categories, at close but non-coincidental intervals (Table 3). In both Brazilian cities of Belo Horizonte and Salvador, conditions inherent to tropical climate obscured defining the lower limits of PET index (°C) for "Comfortable" category. Least of all was it possible to establish the intervals corresponding to negative thermal stress.

Table 3 – PET Index Calibration from different studies in Brazil, Germany and China, in ºC

	Categories	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	Thermal Perception	**Hot**	**Warm**	**Slightly Warm**	**Comfortable**	**Slightly Cool**	**Cool**	**Cold**
	Physiologica l Stress	**Extreme positive stress**	**Strong positive stress**	**Moderate positive stress**	**No thermal stress**	**Moderate negative stress**	**Strong negative stress**	**Extreme negative stress**
	PMV	**3**	**2**	**1**	**0**	**-1**	**-2**	**-3**
Alemanha (KATZSCHNER, 2011)		> 42	35 - 41	29 - 34	18 - 28	13 - 17	< 13	
Hong Kong (KATZSCHNER, 2011)		> 45	35 - 45	30 - 35	12 -30	9 - 12	< 8	
Belo Horizonte (HIRASHIMA, 2010)		> 35.0	30.5 – 35.0	-	≤ 30.5	-	-	
Salvador (FÉ et al, 2007)		-	-	-	≤ 26.6	-	-	
Salvador (Authors)		**≥ 34.1**	**29.4 - 34.1**	26.8 - 29.4 (inference)	**≤ 26.8**	**-**	**-**	

Source: Authors.

Moreover, FÉ et al. (2007) evaluated the applicability of PET Index (°C) with acclimatised high-school students in Salvador, Brazil and concluded that the upper limit of "Comfortable" PET interval was 26.6 °C, matching the upper limit defined in our research.

Researchers in both tropical cities of Belo Horizonte (HIRASHIMA, 2010) and Salvador conducted field research in the same years. Using similar methodology for open spaces in Belo Horizonte, Brazil, Hirashima (2010) delimited three intervals for PET Index (°C): "Comfortable", PET above 30.5 °C; "Warm", PET between 30.5 °C and 35.0 °C; and "Hot", PET above 35.0 °C.

Comparing Belo Horizonte study (HIRASHIMA, 2010) with outcomes of this work, Categories "Hot" and "Warm" yielded approximate results. Furthermore, Hirashima (2010) did not establish the "Slightly Warm" category, consistent with our result at 50% criterion of DT responses. Nonetheless, for DT 30% of responses, our study inferred limits for "Slightly Warm", with PET interval between 26.8 and 29.4 °C.

Consistently, the "Comfortable" upper limit found in this study, corroborated by Fé et al. (2007), contrasts with similar studies developed for the temperate climate in Germany and sub-tropical in Hong Kong. The former obtained PET intervals for "Comfortable" between 18 to 28 °C and 12 to 30 °C, respectively, whereas Matzarakis et al. (1999) proposed PET lower and upper limits of 18 to 23 °C for the same category. Similarly, "Hot" and "Warm" categories reached higher PET values than the equivalent categories in the tropical cities of Salvador and Belo Horizonte.

This work suggests that thermal perception of acclimatised people to the specific tropical conditions with small daily and annual climatic variation and prevailing positive thermal stress throughout the year, masks thermal perception and impedes precision of response. Clearly, Belo Horizonte and Salvador did not manage to delimit "Slightly Warm".

6. Conclusions

This study was aimed at calibrating the thermal comfort index PET (°C) for the population of Salvador, Brazil in urban areas by measuring environmental variables and interviewing pedestrians on thermal perception simultaneously.

Decision Tree statistical analyses identified PET sequenced and clear intervals. Interpreting DT results by 50% criterion gave inconclusive determinations for all but one category, “Hot”. Applying a less restrictive criterion of 30% of responses to DT values, the study defined the categories, “Hot” (category 1), PET > 34.1 ºC, “Warm” (category 2), 29.4 < PET≤ 34.1 ºC and “Comfortable” (category 4), PET ≤ 26.8 ºC. “Slightly Warm” (category 3) did not reach the 30% criterion of responses. Yet, the researchers defined this interval by inference (26.8 <PET ≤ 29.4 ºC). Even the 30% criterion was not sufficient to determine the lower limit of “Comfortable”, nor “Slightly Cool” (category 5) or the categories related to negative thermal stress. Nonetheless, the upper limit of “Comfortable” set at 26.8 °C indicates a significant result for Salvador due to predominance of positive thermal stress conditions throughout the year. In conclusion, this study proposes the PET index ≤ 26.8 °C as the upper limit for the “Comfortable” category for the city of Salvador.

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