Calibration of outdoor thermal comfort models

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ABSTRACT: This research focuses the calibration of predictive models of outdoor thermal comfort through field studies. The objective is to verify their applicability in outdoor spaces of Grande Sao Paulo, a Brazilian metropolitan area with over 18 million inhabitants. The method adopted is experimental inductive (field research of micro-climatic variables and subjective answers) and deductive (simulation and calibration of predictive models). The field research consists of 36 different micro-climatic scenarios and over 900 applied questionnaires (these field studies are considered in another paper whose abstract was also sent for evaluation). The calibrations were done for twenty predictive models, which were originally developed by: Houghten (1923), Vernon & Warner (1932), Siple & Passel (1945), Belding & Hatch (1955), Yaglou (1957), Masterton & Richardson (1979), Gagge (1967), Givoni (1969), Jendritzky (1979), Domínguez (1992), Brown & Gillespie (1995), Aroztegui (1995), Blazejczyk (1996), Höppe (1999), Givoni & Noguchi (2000), Bluestein & Osczevski (2002), Jendritzky (2003), Nikolopoulou (2004). All the predictive models were computationally processed and the results of the simulations are compared to the results of the empirical field survey, calibrating the models and allowing them to be properly used to assess thermal comfort in outdoor spaces of Grande Sao Paulo, Brazil.

Keywords: thermal comfort, outdoors, predictive models, calibration

1. INTRODUCTION

Evaluating outdoor spaces requires the comprehension of additional factors, which are not taken into account in a typical indoor situation, such as solar radiation and winds, considerable sweating rates or heavy clothes, different human activities and expectations, bringing more complexity to the thermal analysis. This paper will present the results of a research focusing the calibration of predictive models of outdoor thermal comfort through field studies. The objectivity is to verify the applicability of the models, calibrating them to be properly used to assess thermal comfort in outdoor spaces of Grande Sao Paulo, Brazil.

2. METHODS

The method adopted is experimental inductive (field research of micro-climatic variables and subjective answers) and deductive (simulation and calibration of predictive models).

The field research consists of 36 different micro-climatic scenarios and over 900 applied questionnaires. For the measurements and application of questionnaires, three bases were set: the first one under open sky, the second one shaded by trees, and the third one under a membrane tensioned structure.

In each one of the three bases, micro-climatic variables (mean radiant temperature, air temperature, air humidity and wind speed) were measured and a hundred and fifty people answered a questionnaire, in six different hours of the day. The questionnaire considered questions of personal characteristics (sex, age, weight, height), acclimatization (places of living and duration) and subjective responses (thermal sensation, preference, comfort and tolerance). Pictures were taken of everyone who would answer the questionnaire, in order to identify clothing and activity. A forth base, at 10m high, was set for measuring meteorological parameters (global radiation, air temperature and humidity, and wind speed). The procedures were done during the summer and winter.

The simulations considered twenty predictive models and thirty-two different indexes. All the models were computationally processed, based on the works that are briefly presented in the following topic. The results of the simulations were compared to the results of the field researches, according to the criteria that are presented in the subsequent topic, providing the results for the calibration of the models.

3. PREDICITVE MODELS

Houghten et al. [1], of ASHVE laboratories, propose, in 1923, the Effective Temperature (ET), as determined by dry and wet bulb temperature and wind speed. Vernon & Warner [apud 2], in 1932 propose the Corrected Effective Temperature (CET) substituting dry bulb temperature with globe temperature. Siple & Passel [3], in 1965, developed the Wind Chill Temperature (WCT) from the data obtained with experiences in Antarctica. Belding & Hatch [4], in 1965 propose the Heat Stress Index (HSI), relying on a thermal balance model with empirical equations for each exchange. Yaglou & Minard [5], in 1957, proposes the Wet Bulb Globe Temperature (WBGT). ISO 7243:1989 [6] gives an alternate equation for situations under solar radiation.

Gagge [7], in 1967, presents the New Standard Effective Temperature (SET*), defining it as the air temperature in which, in a given reference environment, the person has the same skin temperature (tsk) and wetness (w) as in the real environment. Givoni [8], in 1969, proposes the Index of Thermal Stress (ITS), which considers the heat exchanges, metabolism and clothes. Originally, it did not consider the radiation exchanges. Masterton & Richardson [9], in 1979, propose the Humidex, an index calculated based on air temperature and humidity. It is used by the Environment Canada Meteorological Service to alert people of the heat stress danger. Jendrizky et al. [10], in 1979, developed the Klima Michel Model (KMM). It is an adaptation of Fanger's model [11], with a short wave radiation model, computed in the mean radiant temperature. Vogt [12], in 1981, proposes the evaluation of thermal stress through the required sweat rate (Swreq). This index was adopted by ISO 7933:1989 [13]. Dominguez et al. [14], in 1992, present the research results of the Termotecnia Group of Seville University, also based on Vogt [12]. The authors accepted low sweat rates according to the conditioning required. Brown & Gillespie [15], in 1995, propose an outdoor Comfort Formula based on thermal budget (S) with some particularities in its terms. Aroztegui [16], also in 1995, proposes the Outdoor Neutral Temperature (Tne), based on Humphreys [17] and taking into account the solar radiation and air speed. Blazejczyk [18], in 1996, proposes the Man-Environment Heat Exchange model (Menex), based on thermal balance. The author proposes three criteria, which are supposed to be considered as a whole: Heat Load (HL), Intensity of Radiation Stimuli (R') and Physiological Strain (PhS). He also proposes the Subjective Temperature Index (STI) and the Sensible Perspiration Index (SP). DeFreitas [apud 19], in 1997, presents the Potential Storage Index (PSI) and the Skin Temperature Equilibrating Thermal Balance (STE), both using the Menex Model. Höppe [20], in 1999, defines the Physiological Equivalent Temperature (PET) of a given environment as the equivalent temperature to air temperature in which, in a reference environment, the thermal balance and the skin and core temperatures are the same of that found in the given environment. Givoni & Noguchi [21], in 2000, describe an experimental research of in a park in Yokohama, Japan, and propose the Thermal Sensation Index (TS). Bluestein & Osczevski [22], in 2002, propose the New Wind Chill Temperature (NWCT), through a physical modelling of a face exposed to wind. Nikolopoulou [23], in 2004, presents the works developed by the project Rediscovering the Urban Realm and Open Spaces (RUROS), proposing the the actual sensation vote (ASV).

4. COMPARISON CRITERIA

Three criteria were established for comparing the simulation results with the field research results. The first criterion is the correlation between the results of the model parameter and the results of the thermal sensation responses obtained in the field study. The second criterion is the correlation between the results of the index and the results of the thermal sensation responses obtained in the field study. The last one is the percentage of correct predictions. All the criteria are based on results concerning all the thirty-six different micro-climatic scenarios and the mean thermal sensation responses for each one of the scenarios (over nine-hundred questionnaires were applied). The criteria for interpretation of the indexes can be found on the references of the Table 1. Concerning the indexes based on equivalent temperatures, the criterion for interpretation of the indexes used was the one by De Freitas [19]. Yet the author proposes this one only for effective temperatures, it was used for other equivalent temperatures because no other references were found; except for STI, for which was used Blazejczyk [18]. The results obtained with the original indexes are presented comparatively to those from the calibrated indexes, in the end of this paper (Table 24).

5. CALIBRATION PROCESS

The procedures for calibrating the models are the following. Each index was linguistically compared to seven values (the same used in the field researches): three positive ones (warm, hot, very hot), three negative ones (cool, cold, very cold) and one of neutrality (negative values do not apply for models that consider only hot environments). The calibration was done through iterative method, changing the range limits of each index in order to maximize the correlation between its results and those found in the empirical researches. The calibration could be done, also iteratively, to maximize the percentage of correct predictions. However, it was assumed that is more important to assure the maximization of the correlation between the results of the index and those from empirical data, once this correlation expresses the tendency of correctly predicting other situations. The following topic presents comparatively the ranges from the original indexes and those proposed through calibration. The subsequent topic presents the results for the equivalent temperature indexes, in which, as argued, original indexes were not found.

6. ORIGINAL AND CALIBRATED INDEXES

The tables 1 to 22 present the following original indexes: Wind Chill Temperature (WCT), Heat Stress Index (HSI), Wet Bulb Globe Temperature (WBGT), Index of Thermal Stress (ITS), Humidex (HU), Klima Michel Model (KMM), Required Sweat Rate (Swreq), Skin wetness (w), Required Sweat Rate of Sevilla (Swreq'), Thermal Budget (S), Outdoor Neutral Temperature (Tne), Heat Load (HL), Intensity of Radiation Stimuli (R') and Physiological Strain (PhS), Subjective Temperature Index (STI), Sensible Perspiration Index (SP), Potential Storage Index (PSI), Skin Temperature Equilibrating Thermal Balance (STE) Thermal Sensation Index (TS), New Wind Chill Temperature (NWCT), and Actual Sensation Vote (ASV). The tables also present comparatively the calibration proposed for each index.

Table 1: Wind Chill Temperature Index - WCTI (Siple & Passel [3]) and calibration.

WCTI	Classification
< 0,0	extremely hot
0,0 – 58,3	very hot
58,3 - 116,4	hot
116,4 - 232,7	warm
232,7 - 581,5	comfortable
581,5 - 930,4	cool
930,4 - 1628,2	cold
1628,2 - 2326,0	freezing
> 2326,0	extremely freezing

Calibration	Sensation
< 20	very hot
20 - 70	hot
70 - 120	warm
120 - 360	neutral
360 - 680	cool
680 - 1200	cold
> 1200	very cold

Table 2: Heat Stress Index – HSI (Belding & Hatch, [4]) and calibration.

HSI	Classification
> 100	heat stress
70 - 90	very severe response
40 - 60	severe response
10 - 30	light response
0 – 10	no response

Calibration	Sensation
> 70	very hot
35 a 70	hot
25 a 35	warm
0 a 25	neutral

Table 3: Wet bulb globe temperature - WBGT (Yaglou [5]; ISO 7243:1989 [6]) and calibration.

WBGT	65<M<130W/m^2
30	acclimatized
29	non acclimatized

Calibration	Sensation
> 28,0	very hot
23,5 - 28,0	hot
22,0 - 23,5	warm
18,5 - 22,0	neutral
17,0 - 18,5	cool
13,5 - 17,0	cold
< 13,5	very cold

Table 4: Index of Thermal Stress - ITS (Givoni [8]) and calibration.

ITS	Classification
> 150	stress (hot)
50 ~ 150	strain (hot)
-50 ~ 50	neutrality
-150~-50	strain (cold)
< -150	stress (cold)

Calibration	Sensation
> 90	very hot
70 - 90	hot
50 - 70	warm
0 a 50	neutral
-20 a 0	cool
-40 a -20	cold
< -40	very cold

Table 5: Klima Michel Model - PMV (Jendritzky [10]) 1979) and calibration.

PMV	Classification
> 2,5	very hot
1,5 ~ 2,5	hot
0,5 ~ 1,5	warm
-0,5 ~ 0,5	comfortable
-1,5 ~ -0,5	cool
-2,5 ~ -1,5	cold
< -2,5	very cold

Calibration	Sensation
> 3,3	very hot
1,3 ~ 3,3	hot
0,6 ~ 1,3	warm
-0,9 ~ 0,6	neutral
-1,5 ~ -0,9	cool
-3,5 ~ -1,5	cold
<-3,5	very cold

Table 6: Humidex – HU (Masterton & Richardson [9]) and calibration

Humidex (HU)	Classification
≥ 54	heat stroke
≥ 45	danger
40 - 45	very discomfort
30 - 40	discomfort
≤ 30	no discomfort

Calibration	Sensation
> 34,0	very hot
30,5 - 34,0	hot
30,0 - 30,5	warm
< 30,0	neutral

Table 7: Required sweat rate - Swreq (Vogt et al. [12]; ISO 7933:1989 [13]) and calibration.

Swreq	M>65 W/m^2
400	danger (acclimatized)
300	warning (acclimatized)
250	danger (non acclimatized)
200	warning (non acclimatized)
Calibration	**Sensation**
> 160	very hot
90 -160	hot
40 - 90	warm
0 - 40	neutral

Table 8: Wetdness - w (Vogt et al. [12]; ISO 7933:1989 [13]) and calibration.

w max	M>65 W/m^2
1,0	danger
0,85	danger (non acclimatized)
Calibration	**Sensation**
> 0,63	very hot
0,43 - 0,63	hot
0,26 - 0,43	warm
0 - 0,26	neutral

Table 9: Thermal Budget - S of COMFA (Brown & Gillespie [15]) and calibration.

S	Would prefer
> 150	much more cold
50 ~ 150	more cold
- 50 ~ 50	no change
-150~-50	more hot
< -150	much more hot
Calibration	**Sensation**
> 110	very hot
55 ~ 110	hot
15 ~ 55	warm
-23 ~ 15	neutral
-55 ~ -23	cool
-125~-65	cold
< -125	very cold

Table 10: Exterior neutral temperature - Tne (Aroztegui, [16]) and calibration.

Tne - tar	Classification
2,5 ~ 3,5	80% satisfied
-2,5 ~ 2,5	90% satisfied
-3,5 ~ 3,5	80% satisfied
Calibration	**Sensation**
> 11,5	very hot
8,0 ~ 11,5	hot
4,5 ~ 8,0	warm
-4,5 ~ 4,5	neutral
-8,0 ~ -4,5	cool
-11,5 ~ -8,0	cold
< -11,5	very cold

Table 11: Heat Load - HL (Blazejczyk [18]) and calibration.

HL	Stress
≥1,600	very hot
1,186 - 1,600	hot
0,931 - 1,185	neutrality
0,811 - 0,930	cold
≤ 0,810	very cold
Calibration	**Sensation**
≥ 1,80	very hot
1,26 - 1,80	hot
1,08 - 1,26	warm
0,87 - 1,08	neutral
0,83 - 0,87	cool
0,79 - 0,83	cold
≤ 0,79	very cold

Table 12: Physiological strain - PhS (Blazejczyk et al. [19]) and calibration.

PhS	Strain
< 0,25	extr. (hot)
0,25 - 0,49	great (hot)
0,50 - 0,99	slight (hot)
1,00 - 1,99	slight (cold)
2,00 - 4,00	great (cold)
>4,00	extr. (cold)
Calibration	**Sensation**
< 0,25	very hot
0,25 - 0,50	Hot
0,50 - 1,00	warm
1,00 - 3,10	neutral
3,10 - 3,60	cool
3,60 - 4,60	cold
> 4,60	very cold

Table 13: Expected clothing insulation - ECI (Blazejczyk et al. [19]) and calibration.

ECI	Classification
< 0,3	very hot
0,3 - 0,5	hot
0,5 - 0,8	warm
0,8 - 1,2	comfortable
1,2 - 2,0	cool
2,0 - 3,0	cold
> 3,0	very cold

Calibration	Sensation
< 0,34	very hot
0,34 - 0,48	hot
0,48 - 0,52	warm
0,52 - 0,88	neutral
0,88 - 1,50	cool
1,50 - 2,20	cold
> 2,20	very cold

Table 14: Subject Temperature Index - STI (Blazejczyk et al. [19]) and calibration.

STI	Classification
≥ 55,0	very hot
46,0 a 54,9	hot
32,0 a 45,9	warm
22,6 a 31,9	comfortable
- 0,4 a 22,5	cool
-38,0 a -0,5	cold
≤ - 38,0	very cold

Calibration	Sensation
> 75	very hot
55 a 75	hot
35 a 55	warm
15 a 35	neutral
- 5 a 15	cool
-35 a -5	cold
< -35,0	very cold

Table 15: Sensible perspiration - SP (Blazejczyk et al. [19]) and calibration.

SP	Classification
6	completely wet clothing
5	almost completely wet
4	partially wet clothing
3	wet forehead
2	visible humidity
1	wet skin
0	dry forehead

Calibration	Sensation
3,2	very hot
2,0	hot
1,1	warm
0	neutral

Table 16: Radiation Stimuli - R' (Blazejczyk et al. [19]) and calibration.

R'	Stimuli
> 120	weak
60 - 120	mid
< 60	strong

Calibration	Sensation
> 130	very hot
50 - 130	hot
< 50	neutral or warm

Table 17: Potentional Storage Index - PSI (De Freitas, [apud 19]) and calibration.

PSI (W/m^2)	Sensation
< -281	extremely hot
-281 ~ -185	very hot
-184 ~ -111	hot
-110 ~ -50	warm
-49 ~ +16	comfortable
17 ~ 83	cool
84 ~ 161	cold
162 ~ 307	very cold

Calibration	Sensation
< - 115	very hot
-115~ - 52	hot
- 52 ~ - 22	warm
- 22 ~ 22	neutral
22 ~ 52	cool
52,0 ~ 115	cold
> 115,0	very cold

Table 18: Skin temperature - STE (De Freitas [apud 19]) and calibration.

STE (°C)	Sensation
> 35.2	extremely hot
34.5 - 35.2	very hot
33.4 - 34.4	hot
32.2 - 33.3	warm
30.9 - 32.2	comfortable
29.1 - 30.8	cool
26.0 - 29.0	cold
21.1 - 25.9	very cold
< 21.1°C	extremely cold

Calibration	Sensation
> 33,7	very hot
32,5 - 33,7	hot
32,0 - 32,5	warm
30,3 - 32,0	neutral
28,7 - 30,3	cool
25,8 - 28,7	cold
< 25,8	very cold

Table 19: Required sweat rate - Swreq (Dominguez et al. [14]) and calibration.

Sweat rate	Classification
< 90 g/h	walking
< 60 g/h	Staying

Calibration	Sensation
> 280 g/h	very hot
< 280 g/h	Hot
< 130 g/h	warm
< 70 g/h	neutral

Table 20: Thermal Sensation - TS (Givoni et al. [21]) and calibration.

TS	Classification
7	very hot
6	hot
5	warm
4	neutrality
3	cool
2	cold
1	very cold

Calibration	Sensation
6,7	very hot
5,6	hot
4,7	warm
4,0	neutral
3,3	cool
2,4	cold
1,3	very cold

Table 21: New Wind Chill Temperature Index - NWCTI (Bluestein & Osczevski [22]) and calibration.

NWCTI	Sensation
> 35	very hot
27 - 35	hot
23 - 27	warm
21 - 23	confortable
17 - 21	cool
9 - 17	cold
< 9	very cold

Calibration	Sensation
> 36	very hot
30 - 36	hot
24 - 30	warm
12 - 24	neutral
6- 12	cool
0 - 6	cold
< 0	very cold

Table 22: Actual Sensation Vote - ASV (Nikolopoulou [23]) and calibration.

ASV	Sensation
> 1,5	very hot
0,5~ 1,5	hot
-0,5~ 0,5	confortable
-1,5~ 0,5	cold
< 1,5	very cold

Calibration	Sensation
> 1,20	very hot
0,40~ 1,20	hot
0,15~ 0,40	warm
-0,15~ 0,15	neutral
-0,15~ -0,40	cool
1,20~ -0,40	cold
< -1,20	very cold

7. CALIBRATION FOR EQUIVALENT TEMPERATURES

The previous topic presented comparatively the ranges from the original indexes and those proposed through calibration. This topic presents the results for the equivalent temperature indexes, in which, as mentioned before, original indexes were not found. Table 23 presents the calibration for the following equivalent temperatures indexes:

New Effective Temperature (ET*),
New Corrected Effective Temperature (CET*),
Operative Temperature (OT),
New Effective Operative Temperature (EOT*),
New Standard Effective Temperature (SET*),
Physiologically Equivalent Temperature (PET).

Table 23: Proposed calibration for the indexes: ET*, CET*, OT, EOT*, SET*, PET.

Sens.	ET*	CET*	OT
very hot	> 33,0	> 42	> 34
hot	> 27,5	> 35	> 30
warm	> 25,5	> 29	> 26
neutral	21,0-25,5	21-29	20-26
cool	< 21,0	< 21	< 20
cold	< 19,0	< 15	< 16
very cold	< 13,5	< 8	< 12

Sens.	EOT*	SET*	PET
very hot	> 36	> 33	> 43
hot	> 29	> 26	> 34
warm	> 26	> 22	> 26
neutral	21-26	12-22	17-26
cool	< 21	< 12	< 17
cold	< 18	< 8	< 10
very cold	< 11	< 1	< 3

8. COMPARATIVE RESULTS

Table 24 presents the results obtained with the original and calibrated indexes. The first column presents the indexes. The second one gives the correlation between the model parameter and the field research subjective answers. The third one gives the correlation between the original index and the field research subjective answers. The fourth one gives percentage of correct predictions without calibration. The fifth and sixth columns provide the same information of the third and fourth ones, but the results were obtained with the calibration proposed.

Table 24: Correlation modules between filed study results and simulation results (without calibration and with calibration)

Index	A	B	C	B'	C'
ET*	0,73	0,59	44%	0,71	72%
CET*	0,89	0,77	11%	0,85	81%
OT	0,72	0,69	47%	0,72	75%
EOT*	0,70	0,66	42%	0,73	75%
WCTI	0,69	0,64	31%	0,74	78%
HSI	0,83	0,72	68%	0,89	81%
WBGT	0,86	-	-	0,86	89%
SET*	0,89	0,84	28%	0,86	86%
ITS	0,84	0,75	62%	0,89	86%
HU	0,74	0,70	69%	0,78	81%
PMV	0,87	0,82	75%	0,83	86%
PPD	0,70	-	-	0,81	78%
Swreq	0,87	-	-	0,86	83%
W	0,86	-	-	0,86	83%
Swreq'	0,89	0,83	72%	0,89	86%
S'	0,89	0,65	61%	0,87	83%
Tne	0,88	0,70	33%	0,89	86%
HL	0,89	0,76	62%	0,88	83%
PhS	0,81	0,71	28%	0,89	86%
R'	0,86	0,76	69%	0,86	83%
STI	0,87	0,79	53%	0,82	78%
SP	0,89	0,82	78%	0,89	86%
ECI	0,78	0,72	42%	0,80	81%
PSI	0,89	0,76	72%	0,88	83%
STE	0,79	0,71	58%	0,81	83%
PET	0,89	0,78	31%	0,89	86%
TS	0,87	0,84	78%	0,89	89%
NWCTI	0,62	0,60	22%	0,71	72%
ASV	0,85	0,77	76%	0,89	89%

A: Correlation with the model parameter
B: Correlation with the original index
C: Percentage of correct predictions without calibration
B': Correlation with the calibrated index
C': Percentage of correct predictions with calibration

9. FINAL CONSIDERATION

The criteria used to evaluate the model predictions allow successive verifications. The first correlation verifies the possible potential of the model. In other words, it verifies the sensibility of the model, showing how well the model parameter results vary in function to variations of thermal responses. The second correlation does the same, but specifically with the interpretation criteria of the indexes. The final criterion gives the percentage of correct predictions, telling how well the model is performing. Considering the calibration, which proposed new ranges for interpretation of the indexes, we can observe that it provides better correlation with empirical data and consequently greater percentage of correct predictions. Considering the results found, it is more interesting to use a model with a better first correlation (the correlation between the model parameter and the field subject responses) than a one with a greater percentage of correct predictions but with a poor first correlation, because a good first correlation means that the models, once calibrated with empirical data, has a good potential to correctly predict the thermal sensations. Finally, we may say that the main contribution of this research is providing not only the possibility of using different models to assess thermal comfort in outdoor spaces of Sao Paulo, but also knowing how well they respond to such situations.

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