TRANSITIONAL SPACES IN SÃO PAULO, BRAZIL: MATHEMATICAL MODELING AND EMPIRICAL CALIBRATION FOR THERMAL COMFORT ASSESSMENT

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ABSTRACT

This paper presents different thermal comfort models and empirical verification for assessment of the thermal conditions of transitional spaces in the city of São Paulo, Brazil. The method adopted is deductive, performing simulations of predictive models, and experimental inductive, considering field research of micro-climatic variables and subjective answers. The thermal comfort predictive models considered were computationally processed. For the empirical verification, two case studies (one, semi-outdoor; the other, semi-indoor) were took into account, with the application of 886 questionnaires in a total of 24 different micro-climatic conditions. The results of the computational simulations were compared to the ones of the empirical field research. Considering the results found, the most appropriated model showed to be the Neutral Operative Temperature. Using the empirical data gathered, this index was calibrated through the proposal of a new equation for even better predictions of thermal comfort in transitional spaces in São Paulo, Brazil.

KEYWORDS

Thermal comfort, Predictive models, Empirical calibration, Transitional spaces.

INTRODUCTION

Evaluating some complex transitional spaces requires the comprehension of additional factors, which are not commonly taken into account in a typical indoor situation, such as the possibility of solar radiation and winds, and also different human activities and expectations, which brings complexity to the thermal analysis. For example, transitional spaces' physical environments vary by the space type and architectural characteristics. The typical behaviors, as well, are much more complex - sitting, standing, and walking - and varied compared to the sedentary behavior in offices or homes. The expectations are also different, since people do not need to remain in a specific workstation without the possibility of choosing the place to stay.

Considering the environmental and behavior differences, this research focuses on human thermal response to conditions in transitional spaces. This kind of space is understood, in this research, as those areas that are influenced by outdoor climate, yet are somehow clearly defined by architecture, as presented by Chun et al. (2004).

These authors consider three types of transitional spaces: Type 1 is a transitional space contained within a building where conditions are constantly mixed; Type 2 is categorized by an attached, covered space connected to the building; Type 3 transitional space is not attached to a building and is essentially an outdoor room, entirely influenced by how the design of the structure modifies the outdoor climate.

Considering this classification, we present two case studies: the first one, an experimental laboratory, which is more similar to an outdoor space, but has a huge tensioned textile membrane covering it (Type 3 transitional space); the second one, a large studio, which is more similar to an indoor space, but suffers a great influence of outdoor climate, since its roof has a high percentage of transparent elements and there are no external walls in most part of the floor pavement (Type 1 transitional space).

Research studies about thermal comfort in transitional spaces are very few. Jitkhajornwanicha & Pitts (2002) used the ASHRAE (1992) scale to evaluate transitional spaces in Bangkok, correlating the results to the ones from Neutral Temperature (Humphreys, 1975). Aroztegui (1995) revised the Neutral Temperature, considering solar radiation and winds, proposing the Outdoor Neutral Temperature, which was used by the author also for evaluating semi-outdoor spaces. Spagnolo & De Dear (2003) assessed semi-outdoor spaces in Sidney, using, among others, Predicted Mean Vote (Fanger 1970) and New Effective Temperature (ASHRAE, 1992) indexes. Chun & Tamura (2005) performed field studies in underground shopping malls in Japan, applying the seven point ASHRAE scale. Cavalcanti, & Sanches (2005) used the Neutral Operative Temperature (ASHRAE, 2004) for evaluating transitional spaces in Cidade Universitaria. Monteiro & Alluci (2006) assessed transitional spaces in Sao Paulo, performing field studies and using the Heat Load Index (Blazejczyk, 2001).

Considering these references, we opted, for the simulations, to choose the predictive models that were already used in the mentioned researches: New Effective Temperature (TE*), Predicted Mean Vote (PMV), Heat Load Index (HL), Outdoor Neutral Temperature (Tne) and Neutral Operative Temperature (OTn).

The objective of this research is to verify which one of the predictive models presents the better results for evaluating thermal comfort in transitional spaces, calibrating its index for even better predictions in such spaces in the city of São Paulo, Brazil.

SIMULATIONS

New Effective Temperature (ET*)

Houghten et al. (1923), of ASHVE laboratories, propose the Effective Temperature (ET), as determined by dry and wet bulb temperature and wind speed. Researches of Glickman, in 1950; Smith, in 1958 and Givoni, in 1963 (apud Givoni 1969) show that ET superestimates humidity. As a consequence, the reference environment started to be considered with a relative humidity of 50%. Vernon & Warner (1932) propose the Corrected Effective Temperature (CET) substituting dry bulb temperature with globe temperature. The empirical index was adopted by ASHRAE, in 1963, defining the New Effective Temperature (ET*) as the operative temperature of an enclosure at 50% relative humidity that would cause the same sensible plus latent heat exchange from a person as would the actual environment. This index was used by ASHRAE Standard 55, Thermal Environmental Conditions of Human Occupancy, from 1963 to 1992 (ASHRAE 1992). It can be calculated, considering that the Operative Temperature (t_o) is the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non uniform environment, following ASHRAE (2001), through the equations 1 and 2.

$$TE^* = t_o + w \cdot Im \cdot LR \cdot (p_a - 0.5 \cdot p_{sTE^*}) \qquad (1)$$

$$t_o = h_r \cdot t_{rm} + h_c \cdot t_{bs} \ / (h_r + h_c) \qquad (2)$$

where: t_o= operative temperature, in ºC; w= skin wetness, dimensionless; Im= index of clothing permeability, dimensionless; LR= Lewis relation; p_a= vapour pressure, in kPa; p_{sTE^*}= saturation pressure of the new effective temperature, in kPa; t_{rm}= mean radiant temperature, in ºC; t_{bs} = dry bulb temperature, in ºC; h_r= radiant exchange coefficient; h_c= convective exchange coefficient, in W/m^{2}ºC.

Predicted Mean Vote (PMV)

Fanger (1970) assumed that thermal comfort is defined in terms of the physical state of the body rather than that of the environment, suggesting an equation based on a steady state model. The author also developed the predicted mean vote (PMV) based on ASHRAE scale (hot, warm, slightly warm, neutral, slightly cool, cool, cold). PMV can be determined from equations 3, 4 and 5, as presented by the international standard ISO 7730 (1994).

$$\begin{aligned} PMV = {} & (0{,}303\, e^{-0.036M} + 0{,}028) \{(M\text{-}W) - 3{,}05\ 10^{-3} \cdot \\ & \cdot [5733 - 6{,}99\, (M\text{-}W) - p_a] - 0{,}42 \cdot \\ & \cdot [(M\text{-}W) - 58{,}15] - 1{,}7\ 10^{-5}\, M\, (5867 - p_a) - \\ & - 0{,}001\ 4\, M\, (34 - t_a) - 3{,}96\ 10^{-8}\, f_{cl} \cdot \\ & \cdot [(t_{cl} + 273)^4 - (t_{rm} + 273)^4] - f_{cl}\, h_c\, (t_{cl} - t_a) \qquad (3) \end{aligned}$$

$$\begin{aligned} t_{cl} = {} & 35{,}7 – 0{,}028\, (M\text{-}W) - I_{cl} \{3{,}96\ 10^{-8}\, f_{cl} \cdot \\ & \cdot [(t_{cl} + 273)^4 - (t_{rm} + 273)^4] + f_{cl}\, h_c\, (t_{cl} - t_a)\} \qquad (4) \end{aligned}$$

$$h_c = 2.4\, (T_{cl} - T_a)^{0{,}25} \text{ or } h_c = 12.1\, v^{1/2} \text{ (the greater)} \qquad (5)$$

where: M = metabolic rate (W/m^2); W = external work (W/m^2); t_a = air temperature (°C); t_{rm} = mean radiant temperature (°C); v = relative air speed (m/s); p_a = vapor pressure of water vapor (Pa); t_{cl} = surface temperature of clothing (°C); I_{cl} = clothing insulation in clothes (m^2°C/W); f_{cl} = ratio of clothed/nude surface area; h_c = convective heat transfer coefficient (W/m^2°C)

Heat Load Index (HL)

Blazejczyk (1994, apud Blazejczyk 2001) proposes the Man-Environment Heat Exchange (Menex) model, based on thermo-physiological balance. Its specificities are: evaporative loss pondered by sex (1.0 for men; 0.8 for women), radiation exchanges pondered by nebulosity, solar radiation possibly considered by three different models: SolDir, that considers direct, diffuse and reflected solar radiation; SolGlob, that considers global solar radiation; SolAlt, that can be used when there is no solar radiation data. These models consider clothing thermal resistance and pondered albedo of skin and clothes, presenting different equations according to solar elevation and nebulosity. The twelve equations of these models can be found in Blazejczyk (2001). As can be seen, this thermoregulatory predictive model focuses the evaluation of outdoor spaces. The author proposes five criteria for interpretation of results: Heat Load (HL), Intensity of Radiation Stimuli (R') and Physiological Strain (PhS), Subjective Temperature Index (STI) and the Sensible Perspiration Index (SP). The first one was adopted in this work, since, according to the author, it presents better results for general situations. The equations for determining the Heat Load are:

if $S \leq 0$ W/m^2 and $E_{sk} \geq -50$ W/m^2

$$HL = [(S + 360) / 360]\, [2 - 1/(1+R_c)] \qquad (6)$$

if $S > 0$ W/m^2 and $E_{sk} \geq -50$ W/m^2

$$HL = [(S + 360) / 360]\, [2 + 1/(1+R_c)] \qquad (7)$$

if $S > 0$ W/m^2 and $E_{sk} < -50$ W/m^2

$$HL = (E/\text{-}50)\, [(S + 360) / 360]\, [2 + 1/(1+R_c)] \qquad (8)$$

if $S \leq 0$ W/m^2 and $E_{sk} < -50$ W/m^2

$$HL = (E/-50)\ [(S + 360) / 360]\ [2 - 1/(1+R_c)] \qquad (9)$$

where: S = heat storage; R_c = short wave radiation; E_{sk} = evaporative skin losses; all in W/m^2

Outdoor Neutral Temperature (Tne)

Aroztegui (1995) proposes the adaptive model of Outdoor Neutral Temperature, based on Humphreys (1975), who proposed the concept of Neutral Temperature (Tn). This is defined as the average thermal neutrality temperature to a given population. The Neutral Temperature is linearly related to mean monthly outdoor air temperature (tmm). It is valid indoors with low air speeds and mean radiant temperature close to air temperature (18,5~28,5 ºC). This adaptive model considers that, beyond the automatic processes of thermo-physiological regulation, there is a suite of adaptive responses which enable people to adapt to indoor and outdoor climates by means of behavioural adjustments (clothing, windows, fans), physiological adaptations (acclimatization), and psychological adjustments (expectations). Considering this, and based on Givoni (1969), Aroztegui (1995) took also into account the solar radiation and air speed. For sedentary activity, clothing resistance of 0,8 clo and relative humidity between 35% and 65%, the author established the Outdoor Neutral Temperature Tne, which is presented in the equation 9. For different human activities, the following corrections can be applied: light work (M=210W), -2,0ºC; moderate work (M=300W), -4,5ºC; heavy work (M=400W), -7,0ºC.

$$Tne = 3{,}6 + 0.31\ tmm + \{100 + 0{,}1\ Rdn \cdot \cdot [1 - 0{,}52\ (v\ 0{,}2 - 0{,}88)]\} / 11{,}6\ v\ 0{,}3 \qquad (10)$$

where: tmm = mean monthly temperature, in ºC; Rdn = direct solar radiation, W/m^2; v = air speed, in m/s.

Neutral Operative Temperature (OTn)

ASHRAE 55 (2004) adopts a new standard index for non conditioned environments, the Neutral Operative Temperature, based on the works of De dear at al. (1997). The adaptive model concept, according to these authors, is that the human body not only maintains thermal equilibrium with its environment by means of physiological thermoregulation, but also there is a suite of adaptive responses which enable building occupants to adapt to indoor and outdoor climates by means of behavioral, physiological and psychological adjustments. A total of about 22,000 sets of data have been included in the RP-884 database (De Dear at al. 1997). Based on the acceptable operative temperature ranges for naturally conditioned spaces presented by ASHRAE (2004), equation 10 is presented. A tolerance range of ±2,5 ºC means a 90% of satisfaction, and ± 3,5 ºC, 80%. The model considers people's clothing adaptation in naturally conditioned spaces by relating the acceptable range of indoor temperatures to the outdoor climate, so it is not necessary to estimate the clothing values for the space, neither the humidity nor air speed limits are required.

$$OTn = 17{,}8 + 0{,}32\ tmm \qquad (11)$$

where: OTn= Neutral Operative Temperature, in ºC ; tmm = mean monthly outdoor air temperature, in ºC.

EMPIRICAL RESEARCHES

On the field researches, two different typologies of transitional spaces were considered: firstly, a semi-outdoor space, which is covered by a fabric membrane, as one may see in Figure 1; secondly, a semi-indoor space, which is a studio of 8m high and its roof has 33% of zenital apertures for natural lightning, as one may see in Figure 2.

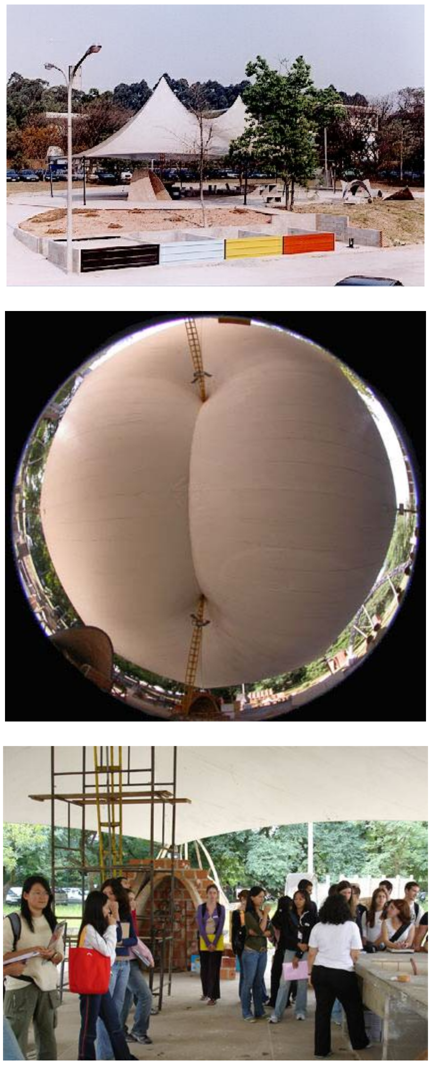


Figure 1 Pictures from the first case study: external view, roof and occupancy.

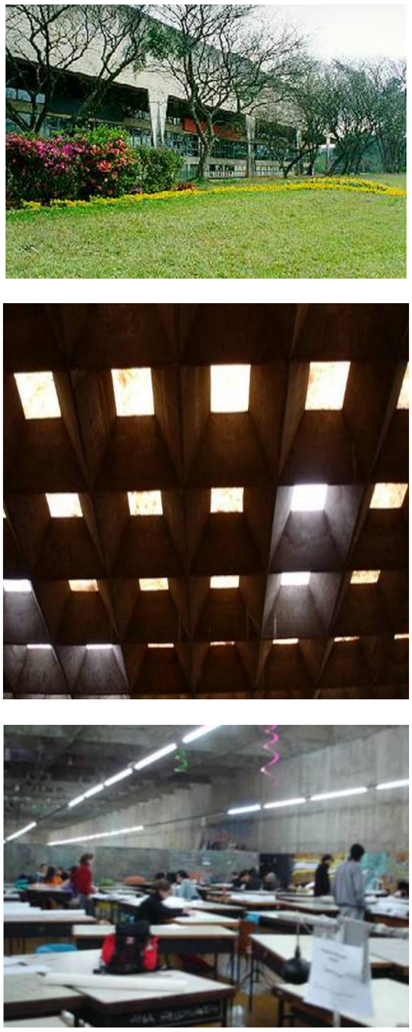


Figure 2 Pictures from the second case study: external view, roof and occupancy.

As a whole, 24 micro-climatic scenarios were considered (twelve in each case), and 886 questionnaires were applied in different hours of summer and winter days. In each one of the cases, micro-climatic variables (mean radiant temperature, air temperature, air humidity and wind speed) were measured along several days during winter and summer. The questionnaire considered questions of personal characteristics (gender, 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. The equipment used under the membrane was a meteorological station ELE model EMS, data logger ELE model MM900 EE 475-016; in the studio a station Innova 7301, with modules of thermal comfort and stress, and data logger Innova model 1221 were used. In each case, globe temperature was also measured through 15cm grey globes and semiconductor sensors, storing the data in Hobo data loggers. The measurements were done in intervals of 1 second, and the storage was done in intervals of 1 minute, considering the average of measurements.

EMPIRICAL RESULTS

Figure 3 presents the environmental data obtained in the semi-outdoor space, under the membrane tensioned structure. The data was gathered in four representative days, two of them in the summer and the other two in the winter. The mean temperature was 21,1°C for the summer month and 17,8°C for the winter one.

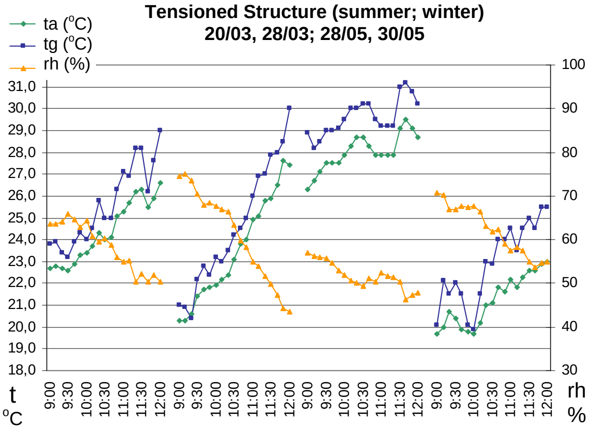
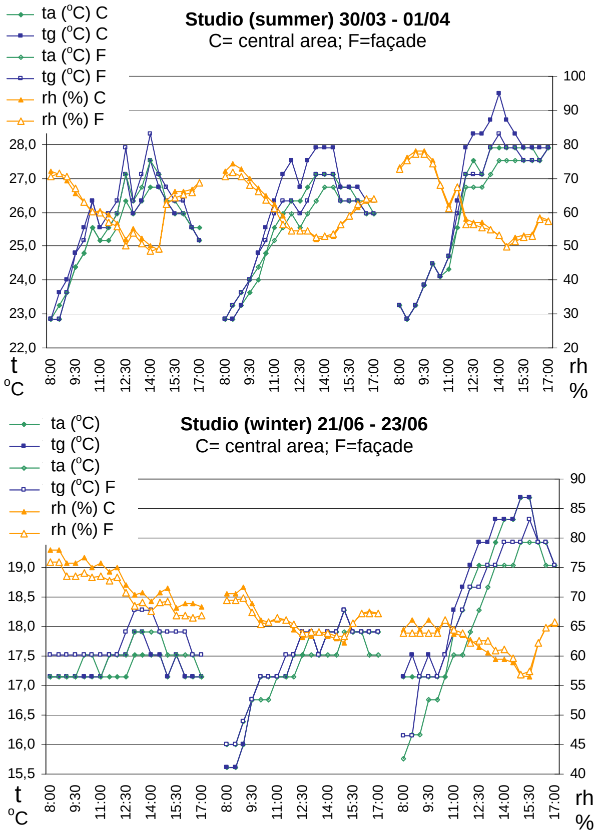


Figure 3 Environmental data under the membrane tensioned structure (summer and winter conditions)

Figures 4 and 5 presents the environmental data obtained for the semi-indoor space, the studio with zenital apertures. The data was gathered in four consecutive days of summer (Figure 4) and four consecutive days of winter (Figure 5). The mean temperature for the summer month was 21,1°C and for the winter month 17,1°C.

Table 1 presents the enviromental data collected, specifically in the periods in which the questionnaires were applied. In this table one may found: TM = space under the tensioned textile membrane; SC = center of studio; SF = near to the façade of the studio; t_a = air temperature, in °C; rh = relative humidity, in %; v = relative air velicity, in m/s; t_g = globe temperature, in °C; t_{rm} = mean radiant temperature, in °C.

Table 2 presents the individual and subjective data collected. The individual data are: N = number of applied questionaires, M = metabolic rate (estimated by kind of activity), in W/m^2; I_{cl} = clothing thermal insulation (estimated by pictures taken of each subject), in clo. The subjective data are: Sens = thermal sensation (-3, -2, -1, 0, 1, 2, 3; from cold to hot); Comf = thermal comfort (0, 1, 2, 3; from totally comfortable to very uncomfortable); Pref = preferred thermal sensation (-3, -2, -1, 0, 1, 2, 3; from cold to hot); Tol = tolerance to the environment (0, 1, 2, 3; from perfectly bearable to completely unbearable).



Figures 4 & 5 Environmental data in the studio with zenital apertures (summer and winter conditions)

Table 1 Enviromental data collected

	site	date	time	t_a °C	rh %	v m/s	t_g °C	t_{rm} °C
1	TM	28/3	09:20	22,7	64	0,38	23,4	24,1
2	TM	28/3	09:40	22,9	65	0,45	23,9	24,9
3	TM	28/3	10:00	23,4	64	0,37	24,0	24,5
4	TM	28/3	11:00	25,3	55	0,19	27,1	28,2
5	TM	28/3	11:20	26,2	50	0,51	28,2	30,3
6	TM	28/3	11:40	25,5	50	0,68	26,2	27,1
7	TM	30/5	09:20	20,6	74	0,97	20,4	20,3
8	TM	30/5	09:40	21,7	68	0,62	22,8	23,6
9	TM	30/5	10:00	21,9	68	0,61	23,2	24,2
10	TM	30/5	11:00	24,9	55	0,50	26,0	26,7
11	TM	30/5	11:20	25,8	52	0,41	27,0	27,5
12	TM	30/5	11:40	26,5	47	0,82	28,0	28,7
13	SC	30/3	15:00	26,7	49	0,12	26,7	26,7
14	SC	31/3	15:00	26,7	56	0,12	26,7	26,7
15	SC	01/4	15:00	27,9	53	0,12	28,3	28,4
16	SC	21/6	14:30	17,5	71	0,14	17,5	17,5
17	SC	22/6	14:30	17,9	63	0,14	17,9	17,9
18	SC	23/6	14:30	19,8	59	0,14	19,8	19,8
19	SF	30/3	15:00	27,1	49	0,10	27,1	27,1
20	SF	31/3	15:00	26,3	56	0,10	26,3	26,3
21	SF	01/4	15:00	27,5	51	0,10	27,9	28,0
22	SF	21/6	14:30	17,9	69	0,12	17,9	17,9
23	SF	22/6	14:30	17,5	63	0,12	17,9	18,0
24	SF	23/6	14:30	19,0	60	0,12	19,4	19,6

Table 2 Individual and subjective data collected

	N	M W/m^2	I_{cl} clo	Sens	Comf	Pref	Tol
1	30	76	0,56	0,08	0,32	-0,16	0,52
2	25	76	0,51	0,04	0,21	-0,13	0,54
3	24	76	0,59	-0,17	0,10	0,27	0,30
4	26	76	0,55	0,69	0,50	-0,46	0,69
5	24	76	0,52	0,38	0,29	-0,58	0,38
6	27	76	0,53	0,15	0,11	-0,44	0,56
7	23	76	0,66	-0,27	0,27	0,27	0,41
8	22	76	0,73	-0,23	0,41	0,05	0,41
9	22	76	0,66	0,17	0,39	-0,39	0,48
10	22	76	0,64	0,41	0,45	-0,32	0,41
11	24	76	0,56	0,30	0,26	-0,39	0,26
12	23	76	0,60	0,67	0,42	-0,88	0,58
13	43	70	0,47	1,51	1,16	1,42	1,36
14	22	70	0,42	1,32	1,05	1,41	0,95
15	47	70	0,47	2,02	1,74	1,89	1,84
16	71	70	0,74	-1,42	0,96	-1,39	1,23
17	65	70	0,75	-1,02	0,82	-0,98	1,09
18	49	70	0,66	-0,22	0,41	-0,29	0,61
19	43	70	0,47	1,51	1,16	1,42	1,36
20	22	70	0,42	1,32	1,05	1,41	0,95
21	47	70	0,47	2,02	1,74	1,89	1,84
22	71	70	0,74	-1,42	0,96	-1,39	1,23
23	65	70	0,75	-1,02	0,82	-0,98	1,09
24	49	70	0,66	-0,22	0,41	-0,29	0,61

SIMULATIONS RESULTS

Considering the data from Table 1 (t_a, rh, v, t_g and t_{rm}) and Table 2 (M and I_{cl}), simulations were performed considering the models presented before. One may notice that not all variables apply to all the models. The results from the simulations are presented in Table 3.

This table also presents the Pearson Product Moment correlation (r) between the results from the simulations and the ones from the empirical research that can be found in Table 2 (Sens). The consideration of the results of the other subjective answers (Comf, Pref and Tol) will be object of a further publication.

In Table 3, one may find the results from the following simulations with the following models are presented: Effective Temperature (ET*), Predicted Mean Vote (PMV), Heat Load (HL), Outdoor Neutral Temperature (Tne), and Neutral Operative Temperature (OTn).

The interpretations for their results are also provided, considering the indexes originally presented in the literature mentioned in the beginning of this paper.

Table 3 Results from different models simulations (ET, PMV, HL, Tne, OTn) and their Pearson Product Moment correlation (r).*

	ET*	Sensation	**PMV**	Sensation	**HL**	Sensation	***d*Tne**	Satisfied	***d*OTn**	Satisfied

	°C		-		-		°C	%	°C	%
1	23,9	warm	-0,14	neutral	0,97	cool	2,2	> 90%	0,08	> 90%
2	24,5	warm	-0,23	neutral	0,95	cool	2,9	> 80%	0,04	> 90%
3	24,6	warm	0,10	neutral	1,00	neutral	3,2	> 80%	-0,17	> 90%
4	27,4	hot	0,82	warm	1,05	warm	9,1	<< 80%	0,69	> 90%
5	29,1	hot	0,73	warm	1,10	warm	11,4	<< 80%	0,38	> 80%
6	27,1	hot	0,28	neutral	1,05	warm	6,1	<< 80%	0,15	> 90%
7	20,9	cool	-0,85	cool	0,88	cool	-3,9	< 80%	-0,27	< 80%
8	23,4	warm	-0,17	neutral	1,03	warm	-1,5	> 90%	-0,23	> 90%
9	23,9	warm	-0,26	neutral	1,01	neutral	-1,3	> 90%	0,17	> 90%
10	26,3	warm	0,46	neutral	1,08	warm	2,5	> 80%	0,41	> 90%
11	27,1	hot	0,60	warm	1,07	warm	4,1	< 80%	0,30	> 80%
12	27,8	hot	0,64	warm	1,07	warm	2,7	> 80%	0,67	> 80%
13	26,7	warm	0,78	warm	1,00	neutral	6,6	<< 80%	1,51	> 90%
14	27,1	hot	0,76	warm	0,96	cool	6,7	<< 80%	1,32	> 90%
15	28,5	hot	1,17	warm	1,05	warm	7,8	<< 80%	2,02	> 80%
16	17,7	cool	-0,79	cool	0,86	cool	-2,5	> 80%	-1,42	<< 80%
17	18,1	cool	-0,72	cool	0,87	cool	-2,0	> 90%	-1,02	<< 80%
18	20,0	cool	-0,52	cool	0,88	cool	-0,4	> 90%	-0,22	< 80%
19	27,1	hot	0,93	warm	1,01	neutral	11,3	<< 80%	1,51	> 90%
20	26,7	warm	0,71	warm	0,94	cool	10,6	<< 80%	1,32	> 90%
21	28,8	hot	1,10	warm	1,03	warm	11,0	<< 80%	2,02	> 80%
22	18,1	cool	-0,65	cool	0,87	cool	3,0	> 80%	-1,42	<< 80%
23	18,1	cool	-0,70	cool	0,87	cool	3,2	> 80%	-1,02	<< 80%
24	19,6	cool	-0,58	cool	0,87	cool	5,0	<< 80%	-0,22	<< 80%
r	**0,80**		**0,79**		**0,83**		**0,75**		**0,85**	

DISCUSSION

Considering the results presented in Table 3, one may affirm that, among the considered indexes, the Neutral Operative Temperature (OTn) had the best correlation with the empirical data gathered (0,85).

The Heat Load index (HL) has a close correlation (0,83) to the OTn one. It presented better correlation than Predicted Mean Vote, which is also based on thermo physiological model, probably because it was developed to outdoors, considering solar radiation, higher wind speeds and most significant sweat rates, which are not well considered by the model proposed by Fanger (1970) that is typically for indoor situations close to thermal comfort conditions.

On the other hand, we must consider that the mathematical modeling of Menex (the model used to calculate the Heat Load Index) is far more complex than the one from Neutral Operative Temperature, that is based on simple equations. So, although the results are close, we would recommend the usage of OTn, mainly because it is much simpler to apply, but also because it presented slightly better results.

The other indexes presented poorer correlations. Despite the fact that the Effective Temperature (ET*) is a quite old empirical index, which has been already abandoned by ASHRAE standards, it presented a considerable correlation of 0,80.

The Predicted Mean Vote (PMV) showed to be even poorer than the Effective Temperature to predict thermal adequacies of transitional spaces, presenting a correlation with the empirical that of 0,79. Last, the Outdoor Neutral Temperature (Tne) provided the poorest results, with a correlation of just 0,75. This adaptive model was developed based on Humphreys (1975) adaptive model, but the consideration of solar radiation and winds were done just theoretically, considering the studies of Givoni (1969). The theoretical assumptions seems not to work in the case of transitional spaces in São Paulo, Brazil.

The PMV, developed by Fanger and used in many standards, such as ISO (1994) and now by ASHRAE (2004), seems to not work properly in the assessment of transitional spaces. That is probably the reason why ASHRAE (2004) proposes an optional method for determining acceptable thermal conditions in naturally conditioned spaces. In such spaces, we have much more influence of outdoors climate than in mechanical air conditioned spaces. The proposed index, based on a Neutral Operative Temperature, showed good results for assessing transitional spaces in São Paulo.

As a consequence, in the next topic we are going to present a calibration of such index, based on the empirical data gathered, in order to provide even better predictions of thermal adequacy of transitional spaces in the specific case of the city of São Paulo.

CALIBRATION

A calibration process was applied in order to maximize the correlation between the Neutral Operative Temperature and the subjective responses presented in table 2, related to the perception of thermal sensation and the satisfaction with thermal environment. Equation 11 presents the proposed calibration, considering the empirical data gathered.

$$OTn^{*}= 20{,}6 + 0{,}15\ tmm \qquad (12)$$

This equation provides results with a Pearson Product Moment correlation (r) = 0,87 ($p < 0{,}01$), against 0,85 of the original one.

Table 4 presents the new results applying the original (OTn) and the proposed equation (OTn*) for assessing thermal comfort in transitional spaces in São Paulo, Brazil.

Table 4 Results from the original Neutral Operative Temperature equation (OTn) and from the proposed equation (OTn) for assessing thermal comfort in transitional spaces in São Paulo, Brazil.*

	t_{mm}	t_o	OTn	*d*	%	OTn*	*d**	%
1	21,1	23,4	24,6	-1,2	> 90	23,8	-0,4	> 90
2	21,1	23,9	24,6	-0,7	> 90	23,8	0,1	> 90
3	21,1	24,0	24,6	-0,6	> 90	23,8	0,2	> 90
4	21,1	26,8	24,6	2,2	> 90	23,8	3,0	> 80
5	21,1	28,3	24,6	3,7	< 80	23,8	4,5	< 80
6	21,1	26,3	24,6	1,7	> 90	23,8	2,5	> 80
7	17,8	20,5	23,5	-3,0	> 80	23,3	-2,8	> 80
8	17,8	22,7	23,5	-0,8	> 90	23,3	-0,6	> 90
9	17,8	23,1	23,5	-0,4	> 90	23,3	-0,2	> 90
10	17,8	25,8	23,5	2,3	> 90	23,3	2,5	> 80
11	17,8	26,7	23,5	3,2	> 80	23,3	3,4	> 80
12	17,8	27,6	23,5	4,1	< 80	23,3	4,3	< 80
13	21,1	26,7	24,6	2,2	> 90	23,8	3,0	> 80
14	21,1	26,7	24,6	2,2	> 90	23,8	3,0	> 80
15	21,1	28,2	24,6	3,6	< 80	23,8	4,4	< 80
16	17,1	17,5	23,3	-5,8	<<80	23,2	-5,6	<<80
17	17,1	17,9	23,3	-5,4	<<80	23,2	-5,3	<<80
18	17,1	19,8	23,3	-3,5	> 80	23,2	-3,4	> 80
19	21,1	27,1	24,6	2,6	> 80	23,8	3,4	> 80
20	21,1	26,3	24,6	1,8	> 90	23,8	2,6	> 80
21	21,1	27,8	24,6	3,2	> 80	23,8	4,0	< 80
22	17,1	17,9	23,3	-5,4	<<80	23,2	-5,3	<<80
23	17,1	17,8	23,3	-5,5	<<80	23,2	-5,4	<<80
24	17,1	19,3	23,3	-4,0	< 80	23,2	-3,9	< 80

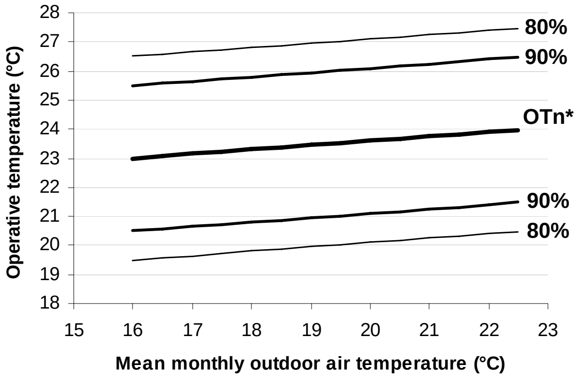
CONCLUSIONS

One may observe that the original index of Neutral Operative Temperature, presented by ASHRAE (2004) is originally intended for assessing thermal conditions in naturally conditioned spaces, and its empirical data is mainly based on researches which took place in office buildings. In such spaces, although there may be a great influence of outdoor climate, typically there are not much influence of direct radiation.

Considering our two case studies, in the studio we have direct solar radiation and under the membrane, we have high sufaces temperatures, due to their exposure to direct solar radiation. As a result, it is possible to see considerable differences in the final results: the original Neutral Operative Temperature varies from 23,3°C and 24,6°C, while the new proposed one varies from 23,2°C and 23,8°C.

As one may observe, the influence of mean monthly outdoor air temperature is lower in our two case studies (the original coefficient was 0,32; the new one is 0,15). It is interesting to observe that, on the one hand, the winter Neutral Operative Temperature is pretty the same, but, on the other hand, the summer one is much lower (0,8°C).

Considering the data from the typical reference year (TRY) for São Paulo, presented by Goulart et al. (1998), the Neutral Operative Temperature for transitional spaces in São Paulo is in a range between 23,0°C and 23,9°C. Figure 6 shows these results.



Figures 6 Acceptable operative temperature ranges for transitional spaces in São Paulo, Brazil.

The typical reference year for São Paulo indicates that the higher mean monthly outdoor air temperature is 22,1°C (February) and the lower 16,0°C (July). Considering that this research worked with mean monthly outdoor air temperatures between 17,1°C and 21,1°C, one may say that future researches should increase this range at least 1°C for the summer and for the winter.

Thus, the results presented are extrapolated in ± 1°C in order to cover all the possible ranges of common mean monthly outdoor air temperatures in the city in study. Further researches should be done to verify the assumed extrapolation, in order to provide even better assessment of thermal comfort conditions in transitional spaces of São Paulo, the greatest Brazilian metropolitan area, with over 18 million inhabitants.

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