2.7 URBAN DESIGN AND THERMAL COMFORT: ASSESSMENT OF OPEN SPACES IN BARRA FUNDA, A BROWNFIELD SITE IN SÃO PAULO, BY MEANS OF SITE MEASUREMENTS AND PREDICTIVE SIMULATIONS

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1. INTRODUCTION

Continuing previous works, this research focus on thermal comfort conditions in different microclimates influenced by the urban design of Barra Funda, a neighborhood in the west side of the city of Sao Paulo, Brazil. Recently, this area was object of investigation for British and Brazilian specialists, including the authors, aiming to explore possibilities of intervention for the proposal of urban realm. Duarte and Goncalves (2006) presented the study field, contextualizing it in the city of Sao Paulo, and discussing questions related to vegetation, morphology, building materials and density. In this research, the objective is to verify the adequacy of different configurations of urban outdoor spaces in Barra Funda, inferring possible correlations between thermal sensations and morphological characteristics, including vegetation, of each outdoor space studied.

2. EMPIRICAL RESEARCH

The adopted method is empirical, by means of field researches considering microclimatic variables, and analytical, performing computational simulations of predictive models. The field research was done during a summer day, at seven different locations, in a walking distance from each other, as seen in Figure 1. The spots indicated in Figure 1 can be seen in detail in Figure 2. Figure 3 brings the sky view factor and the nebulosity conditions for each one of the points of study. In each base, there was a set with a thermohigrometer Homis model 229 and an anemometer Homis model 209. The data was registered in fifteen minutes intervals, between 7am/8am, 10am/11am, 1pm/2pm and 4pm/5pm. The data from the meteorological station (Public Health Faculty of University of Sao Paulo), located 2,7 km far from the area, was also considered in the data assessments. Following, one may find the procedures to the measurement and treatment of the considered variables.

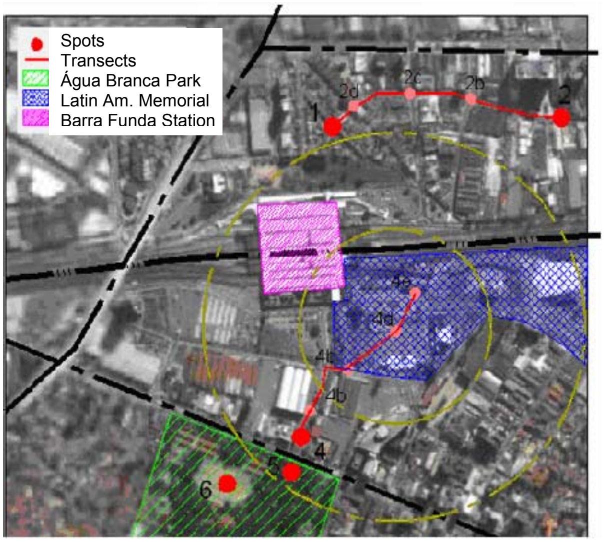

Figure 1: Site of study and points of measurements.

2.1 Air temperature and humidity

Air temperature is a physical quantity that can be measured by several methods, depending on the kind of the sensor that is being used, which temperature can differ from the air temperature due to radiant effects. Therefore, the sensor should be protected from thermal radiation without compromising the proper ventilation in the surroundings of the sensor. ISO 7726 (1998) mentions three strategies to reduce the radiation effect. The first one is reducing the emission factor of the sensor, polishing it or using reflective painting; the second is reducing the temperature difference between the sensor and the surroundings using reflective surfaces of 0,1/0,2mm of thickness; the last one is increasing the convection coefficient, increasing mechanically the air speed around the sensor and/or reducing the sensor size.

Figure 2: Spots of measurements and transects.

In this research, digital thermohigrometers Homis 229 were used, which were calibrated comparing their results with a calibrated one. The sensors were protected from direct solar radiation by means of polystyrene with external aluminized surface and perforations of better convection thermal exchanges. The measurements were taken at 1,1m of height. The sensors used for quantifying the air temperature are semiconductors, with reading range of -20 ºC / +60 ºC, resolution of 0,1 ºC, precision of ± 0,4 ºC and response time of 0,1 ºC/s. The humidity sensors are of capacitance, obtaining the relative humidity. The reading range from 10% to 95%, with resolution of 0,1%, precision of ± 3% (at 25 ºC, between 30% and 95%) and ± 5% (at 25 ºC, between 10% and 30%) and response time of 3 minutes (from 45% to 95%) and 5 minutes (from 95% to 45%). Considering the relative humidity (rh) and the air temperature (t_a), the partial vapor pressure (p_v) were obtained.

$$p_v = 6{,}112\ 10\text{^}[7{,}5t_a / (237{,}7 + t_a)] \cdot 0{,}01\ rh \qquad (01)$$

2.2 *Wind speed*

Air velocity is a physical quantity described by its magnitude and direction. ISO 7726 (1998) indicates the need of considering the direction of the flow and the magnitude fluctuation, and also the mean value and the standard deviation during a certain period of time. The helix sensors used present reading range of 0,4m/s-30m/s, resolution of 0,1m/s, and precision of ± 2%+d, in which "d" is the observed value. The data was registered in a ten second interval during one minute, every fifteen minutes. As the helix sensors are unidirectional, the wind direction was determined by a light weight stream. The wind speed (v_a) considered is the arithmetical mean value of the instantaneous values obtained. In order to consider the magnitude fluctuation, the standard deviation (sd) is estimated, where: n = number of instantaneous measurements, considering Σ from i = 1 till i = n. The turbulence intensity (it) is given in percentage.

$$dp = [1/(n-1)]^{1/2} \cdot \Sigma^{n}_{i=1} (v_{a,i} - v_a)^2 \qquad (02)$$

$$it = 100 \cdot sd/v_a \qquad (03)$$

2.3 Solar radiation

Figure 3 brings the sky view factor and the nebulosity conditions for the points of study.

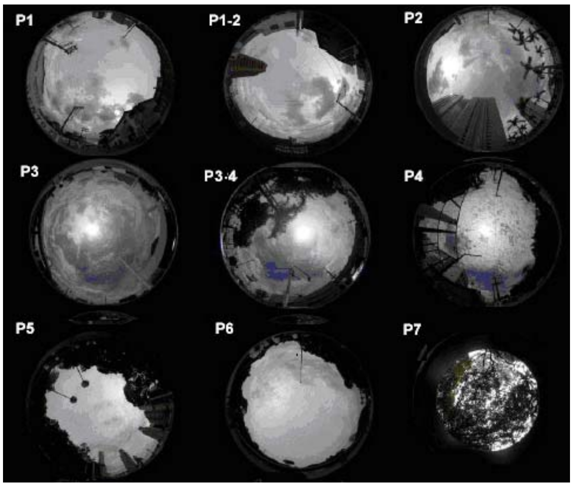

Figure 3: Sky view factor e nebulosity conditions.

In order to consider the solar radiation (Rc) that will be absorbed by the body, Blazejczyk (2002) model was used, which estimates the solar radiation considering the solar height (h) and nebulosity (N), which is between 0 and 1. The variable a' is function of the albedo (a) of the skin/clothing ensemble. An albedo value of 0,5 was adopted.

$h \leq 4°$:

$$Rc = 1{,}4\ a' \cdot (1{,}388 + 0{,}215\ h)^2 \quad (04)$$

$h > 4°$ and $N \leq 0{,}20$:

$$Rc = 1.4\ a' \cdot (-100{,}428 + 73.981 \ln(h)) \quad (05)$$

$h > 4°$ and $N = 0{,}21\text{-}0{,}50$:

$$Rc = 1{,}4\ a' \cdot \exp(5.383 - 16{,}072 / h) \quad (06)$$

$h > 4°$ and $N = 0{,}51\text{-}0{,}80$:

$$Rc = 1{,}4\ a' \cdot \exp(5.012 - 11{,}805 / h) \quad (07)$$

$h > 4°$ and $N > 0{,}80$:

$$Rc = a'\ 0{,}9506 \cdot h^{1{,}039} \quad (08)$$

$$a' = 1 - 0{,}01 \cdot a \quad (09)$$

2.4 Empirical research results

Figure 4 shows the empirical data gathered and treated. These results are considered to perform the predictive simulations.

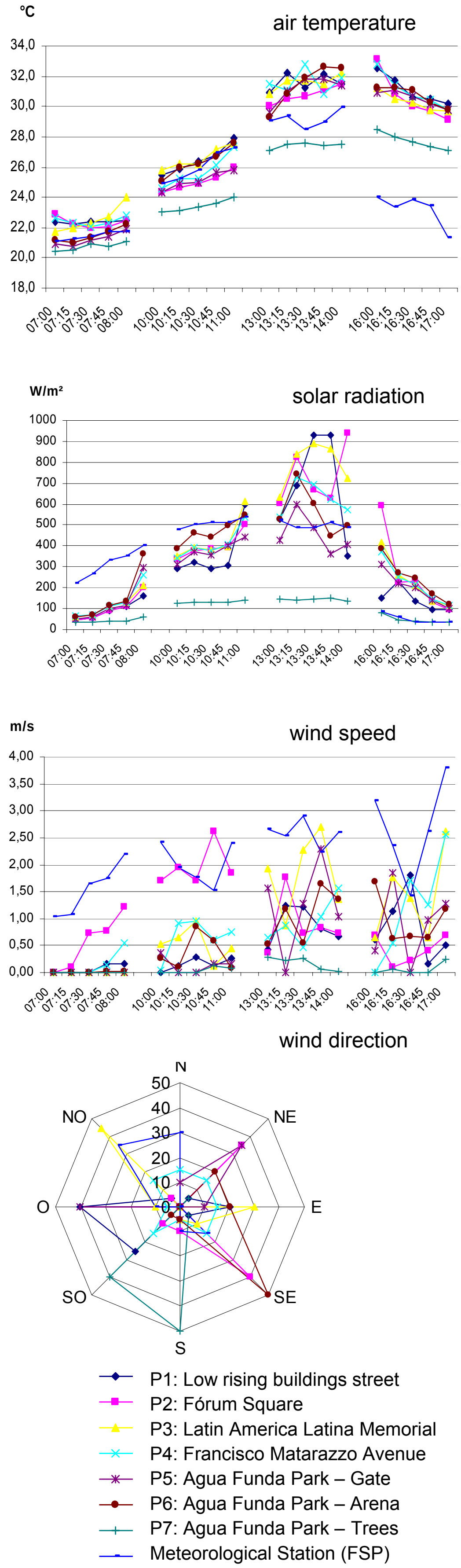

Figure 4: Microclimatic data

3. SIMULATIONS

In order to perform the computational simulations, the thermo physiological balance was adopted, which can be represented as following:

$$S = M + L + Rc + C + K + E_{sk} + Res \qquad (10)$$

Where: S: heat storage in the body, M: metabolic power, Q: heat exchange on the skin by radiation, C: heat exchange on the skin by convection, K: heat exchange on the skin by conduction, E_{sk}: heat loss by evaporation at skin surface, Res: respiration heat loss, all of them in [W/m²]

In this research a metabolic rate M=130W/m^2 was adopted, equivalent to walking at 1 m/s, or 3,6km/h, according ISO 8996 (1990). Considering clothing, a thermal insulation Icl=0,5, equivalent to light trousers, short sleeves shirt, underware and light shoes, was considered, following ISO 9920 (1995).

In the next topics, the following estimations will be considered: (1) mean radiant temperature (trm), (2) superficial skin temperature, and (3) heat load index, in order to assess the thermal conditions of the outdoor spaces in study.

3.1 Mean radiant temperature

The mean radiant temperature (trm) is the uniform surface temperature of a black enclosure with which an individual exchanges the same heat by radiation as the actual environment considered (ASHRAE, 2001). It describes the radiant environment for a point in space. It can be estimated by means of the globe temperature, the two-spheres radiometer, the constant temperature sensor or by the superficial temperatures and angle factors.

In this research, the mean radiant temperature was calculated considering the thermal radiative exchanges between the human body and the sky (Lc) and the surroundings (Lp), considering, as well, the exposure to solar radiation (Rc). In order to determine the surrounding temperature (Tp), air-sun temperature was used, which can be defined as the external superficial temperature that gives the same thermal effect than the combination of the air temperature and the incident thermal radiation.

trm = [(Rc + 0,5 Lc + 0,5 Lp) / (0,95 · 5,667 ·10^-8)]^0,25 - 273 (10)

Lc = 5,5 · 10^-8 (273 + t)^4 [0,82 – 0,25 · 10^(-0,094 · 0,75 v_p)] (11)

Lp = 5,5 · 10^-8 (273 + Tp)^4 (12)

3.2 Skin superficial temperature

In order to estimate the superficial skin temperature, the following equation proposed by Blazejczyk (2004) was applied.

Ts= (26,4 + 0,02138 Trm + 0,2095 t – 0,0185 · ur – 0,009 v) + 0,6 (Icl - 1) + 0,00128M (13)

3.3 Heat Load Index

Blazejczyk (2002) proposes the MENEX, Man-ENvironment heat EXchange model, wich uses the body thermal 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, which considers direct, diffuse and reflect solar radiation; SolGlob, which considers global solar radiation; SolAlt, which 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. In this research, the third model was used; the other two models can be found in Blazejczyk (2004). In order to evaluate the results, it is proposed the criterion based on the Heat Load (HL), which is assessed considering the heat storage (S), absorbed solar radiation (R_C) and evaporative skin losses (E_{sk}).

$S \le 0$ W/m^2 and $E_{sk} \ge -50$ W/m^2

$$HL = [(S + 360) / 360]^{[2 - 1/(1+Rc)]} \qquad (14)$$

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

$$HL = [(S + 360) / 360]^{[2 + 1/(1+Rc)]} \qquad (15)$$

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

$$HL = (E_{sk}/-50) \cdot [(S + 360) / 360]^{[2 - 1/(1+Rc)]} \qquad (16)$$

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

$$HL = (E_{sk}/-50) \cdot [(S + 360) / 360]^{[2 +1/(1+Rc)]} \qquad (17)$$

3.4 Simulation results

Figure 5 presents the simulation results, bringing the values of mean radiant temperature, of skin superficial temperature and of heat load index, for each one of the study points and for the data from the meteorological station.

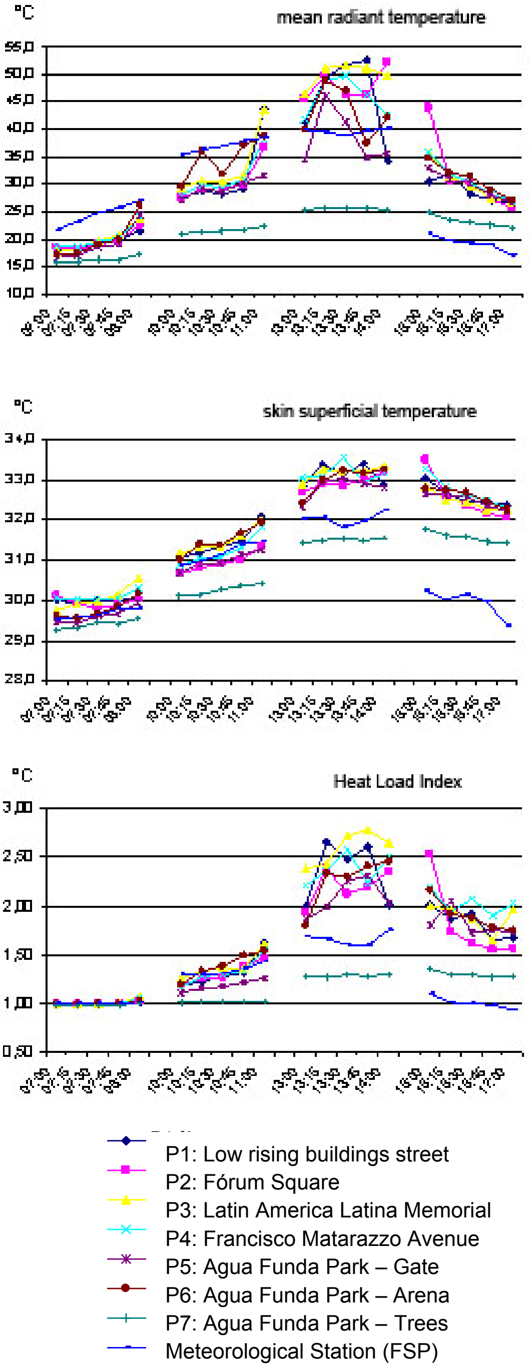

Figure 4: Estimated data

4. EMPIRICAL VERIFICATION/CALIBRATION

Monteiro and Alucci (2006) present empirical research that verifies different outdoor thermal comfort model and indexes. One of the indexes that presented better correlations with the empirical data gathered was Heat Load (correlation of 0,88 for the model parameter and 0,83 for the interpretation of the index). It is observed that the index values presents better correlation that the others, although the interpretation correlation is close to them. On the other hand, as the correlation is better, it is possible to achieve more significant results, by means of the proposal of new interpretative ranges for the index. The same authors (2007) present results of a research in which new interpretative ranges are proposed based on empirical researches carried on the city of Sao Paulo, considering over 70 microclimatic situations and 2000 applied questionnaires. Due to the existence of such calibration done specifically to a population adapted to Sao Paulo climatic conditions, the Heat Load Index was chosen as the criterion for interpreting the results of this research. Table 1 brings the original index (Blazejczyk, 2002) and the proposed calibration by Monteiro and Alucci (2007). The last one was adopted here, as the empirical base was gathered in São Paulo.

Table 1: HL (Blazejczyk, 2002) and calibration proposed by Monteiro & Alucci (2007).

HL	Classification	Calibration	Sensation
		≥ 1,65	very hot
≥1,600	high stress (hot)	1,23-1,65	hot
1,186-1,600	stress (hot)	1,08-1,23	warm
0,931-1,185	neutrality	0,88-1,08	neutral
0,811-0,930	stress (cold)	0,72-0,88	cool
≤ 0,810	high stress (cold)	0,65-0,72	cold
		≤ 0,65	very cold

Other indexes, also calibrated by Monteiro and Alucci (2007), which also presented good results, should be used here, as well. Nevertheless, the Heat Load index was chosen since all the necessary input data was available or was able to be estimated using the MENEX model.

5. FINAL RESULTS

Figure 6 presents the final results of this research, considering the thermal sensations found in each spot of study. In this Figure, N stands for neutrality, W for warm, H for hot, and VH for very hot.

HL	P1	P2	P3	P4	P5	P6	P7	MS
07:00	N	N	N	N	N	N	N	N
07:15	N	N	N	N	N	N	N	N
07:30	N	N	N	N	N	N	N	N
07:45	N	N	N	N	N	N	N	N
08:00	N	N	N	N	N	N	N	N
10:00	W	W	H	W	W	W	N	H
10:15	H	H	H	H	W	H	N	H
10:30	H	H	H	H	W	H	N	H
10:45	H	H	H	H	W	H	N	H
11:00	H	H	H	H	H	H	N	H
13:00	VH	VH	VH	VH	VH	VH	H	VH
13:15	VH	VH	VH	VH	VH	VH	H	VH
13:30	VH	VH	VH	VH	VH	VH	H	H
13:45	VH	VH	VH	VH	VH	VH	H	H
14:00	VH	VH	VH	VH	VH	VH	H	H
16:00	VH	VH	VH	VH	VH	VH	H	W
16:15	VH	VH	VH	VH	VH	VH	H	N
16:30	VH	H	VH	VH	VH	VH	H	N
16:45	H	H	VH	VH	VH	VH	H	N
17:00	H	H	VH	VH	VH	VH	H	N

Figure 6: Final results of thermal sensation for the seven points of study and for the meteorological station.

One may observe in Figure 6, considering the first period of measurements, from 7am to 8am, that all points of study present similar thermal performance, with neutral thermal sensations observed (In Figure 5, one may also notice that all the studied points presented heat load values close to the unity).

During the second period of measurements, from 10 am to 11 am, one may observe the change from the predominant sensation of "warm" to "hot". Two exceptions must be considered, both of them at the Agua Funda Park: P7, under the trees, and P5, in the park gate. In the case of P7, due to the dense shading, as one may observe in Figure 3, there is a smaller sky view factor, resulting in neutrality conditions during the period. At P5, the "warm" condition continues until 10:45am. In this case, the less severe thermal condition is achieved due to a relative smaller sky view factor and to the proximity to the dense vegetation of the park.

The third period of measurements, from 1 pm to 2 pm presents "very hot" situations in all the points of study, except for P7, in which one may find "hot" situations. This point presented the better performance mainly due to the shading from the trees, not only blocking the direct solar radiation but also providing air temperature stability.

During the last period of measurements, from 4pm to 5 pm, one may observe again the predominance of "very hot" situations, except for P7, where the attenuation found is explained for the reasons presented in the last paragraph. The different results found at P2 and P1, where attenuation is found respectively at 4:30pm and 4:45pm, may be explained due to the fact that these points are relatively far from the others, being located in a more uniform horizontal urban tissue. The other points are located in less built areas, but more arid ones, due to pavements used and absence of vegetation (P3 e P4) or inside the park (P5, P6 e P7).

The differences in the results of P1 and P2 can be also explained due to the weather changes in the last period of measurements, as one may conclude observing the results from the meteorological station. Maybe the results of P1 and P2 could be explained because they have a greater sky view factor, contrarily to the park, which was protect by dense vegetation. P3 is also well exposed, but the same difference was not found in this point, following the results of P4, P5 e P6, which are not so exposed. One must mention that measurements were previewed to take place also between 7pm and 8pm, but they were not performed due to the climatic instability. These observations take into account the plausible consideration that, based on the registered data, the instability arrived first at the meteorological station, then to the studied points.

Considering now specifically the results found based on the data from the meteorological station, one may observe that, during the first period of measurements, between 7am and 8am, there are neutrality thermal sensations, in concordance with the results found on the field. This shows that, in the absence of solar radiation, the results from meteorological station seem to be very representative of the general conditions found in the different studied points.

During the second period of measurements, from 10am to 11 am, one may observe “hot” situations, also in accordance with the general results from the field. P5 and P7 are exceptions, as they present smaller sky view factors, respectively because there are shading by high rise buildings and by dense trees. It must be mentioned that, during the first measurement of the second period, the predominant situation was “warm”, whilst the results from the meteorological stations showed a “hot” situation. This can be explained for the fact that all the points present some kind of blockage to the solar radiation during the first hours of the morning, whilst the meteorological station is situated in an unobstructed location. This consideration is corroborated by the results from P3, which presents, during the first measurement of the second period, a situation of “hot”, explained by the fact that there is practically no obstruction in its surroundings.

In relation to the third period of measurements, between 1 pm and 2 pm, there are two situation of “very hot” followed by three of “hot”. Except for P7, which presents dense shading from the trees, all the other studied points presented “very hot” situations during the completely third period. Two questions should be considered. Firstly, as it was said earlier in this work, the climatic instability arrived first at the meteorological station. Secondly, despite the fact that Barra Funda is not a dense built area, it is almost completely paved, presenting considerable thermal capacity, lengthening the period of “very hot” situation.

Finally, during the last period of measurements, from 4 pm to 5 pm, one may observe that the first result from the meteorological station is a “warm” condition, followed by neutrality ones. One may verify here the same tendency pointed out in the last paragraph. If it was possible to perform the measurements from 7 pm to 8 pm, probably results of “hot”, warm” and “neutral” conditions would be consecutively observed in the various points of study, with different time discrepancies due to the geographical location and local thermal inertia from the built environment.

6. FINAL CONSIDERATIONS

Differences in the final results of the studied points were observed, pointing out to possible relationships between urban morphologies and vegetation and the local microclimate, and also to different considerations concerning the environmental adequacy in terms of thermal sensation of the acclimatized population. The results found and the considerations made show the relevance of regarding the urban design and the local treatment of open spaces in order to constitute outdoor spaces that are thermally proper, allowing conditions to the effective use of the urban spaces.

Considering the hot climate, high density constructions showed to allow longer periods in comfort conditions, due to the decrease of the sky view factor and consequently the significant shading effect upon the area. As expected, green areas presented even better results, considering the shading and the evapotranspiration that influences in the thermal comfort sensation. In hot urban environments, the use of higher densities and green areas seems to provide good results not only in the streets, but also when configured as “pocket parks”, which take use of the advantages of both strategies.

This ongoing research has two main development lines, which will be object of future publications. The first one details the thermal analysis done by means of: the verification between the original and the calibrated indexes, the consideration in full detail of the influence of the radiation and ventilation in the microclimatic conditions, and the comparative application of an adaptive model. The second one tests the results found proposing urban interventions, contributing to possible urban redesigns and to the proper design of empty areas in the surroundings of the study area.

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8. ACKNOWLEDGEMENT

We would like to thank all the graduate students that have helped in the empirical research: Anarrita Buoro, Anderson Nedel, Anna Miana, Antonio Machado, Carolina Leite, Daniel Costola, Erica Umakoshi, José Ramos, Juliano Beraldo, Marcos Yamanaka, Monica Marcondes, Paula Shinzato, Rafael Brandao and Sabrina Agostini. We are also thankful to Prof. Koen Stemeers of The Martin Centre for Architectural and Urban Studies, University of Cambridge, and to Prof. Susannah Hagan, of University of East London, for the discussion that preceded this research in meetings financed by The British Academy. Finally, we would like to thank the Fundacao de Amparo a Pesquisa do Estado de Sao Paulo for the financial support.