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An integrated approach for ventilation's assessment on outdoor thermal comfort

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ABSTRACT

Modifications of urban structures that are linked to a lack of elements concerning climate interference in Urban Master Plans lead to environmental consequences that contribute to the thermal discomfort of pedestrians. Ventilation is especially relevant in promoting the necessary airing in regions with hot and humid climate, as is the case for the study site. This study aimed to evaluate the effect of ventilation on pedestrians' thermal comfort in coastal regions with hot and humid climates. This analysis was possible using an integrated approach to analyse urban layouts, thermal perception and urban legislation. An Integrated Method for the Analysis of Ventilation was thus proposed. The sampling area consisted of an urban stretch of Orla de Camburi, a seaside district in the city of Vitória, Espírito Santo (Brazil). The method used microclimatic measurements, which were recorded at the same time as questionnaires on thermal sensation were implemented. The field surveys occurred in winter, spring and summer, comprising six days of measurements and a total of 841 respondents. The survey results provide support for the proposal of a scale of wind perception and preference. The results also enabled the proposal of the calibration of the *PET* (Physiological Equivalent Temperature) thermal comfort prediction index to the climate reality of Vitória. Finally, the survey results promoted the creation of a system to evaluate the suitability of the Master Plan concerning issues about ventilation. The results reaffirmed the importance of using an integrated approach to evaluate ventilation considering pedestrians' thermal comfort.

1. Introduction

The urban environment expansion, associated with vertical growth and cities densification, affects urban climate and consequently population's thermal comfort. These changes on urban layouts affects climate variables magnitude and promote the formation of a mosaic of microclimates, which the urban climate is composed. Researchers in various places around the world have conducted urban climate studies. Cities growth and the conurbations they form has exerted a great effect on global climate and microclimate modifications, including natural ventilation [1]. Wind's change of direction and speed, associated to those of urban layouts, is a key element affecting cities climate [2].

Urban ventilation effectiveness depend of winds on several scales and of cities natural and artificial features [3,4]. To assure townspeople's thermal comfort, urban planning must intervene creating enhanced ventilation conditions. In tropical humid climate zones, ventilation is especially important to accelerate heat exchange between man and environment and thus promoting adequate airing. Urban sites arrangement of buildings affects the natural ventilation flow, so does vegetation. The vegetation's effect on airflow is more intense near the ground and depends on planting arrangement and species used [5–7].

One of the challenges to optimise natural ventilation is to define when it is desired or not [8]. Several studies have recognised this subject importance, and thus, several methods have been proposed whose results indicate that local climate features are crucial to establish comfortable ventilation limits. This fact implies global models evaluation inadequacy [8,9]. Cities growth associated with climate issues absence in urban planning instruments generates environmental consequences contributing to climate changes aggravation, especially with temperatures increase and heat islands formation. In addition to constitutional requirements, urban structures growth observed in Brazilian cities reaffirms local planning central role organising governmental actions aimed at collective welfare.

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From bioclimatology viewpoint, Hoppe [10] notes that microclimatic changes are one of urbanisation processes main consequences. Studies on thermal comfort in open spaces are more complex than those performed indoors because these studies involve greater oscillation in climatic conditions [11,12]. Although predictive indices attempt to balance climatic conditions and human thermal comfort, one must pay attention to each person's particularities. There is a wide application of the PET (*Physiological Equivalent Temperature*) index in thermal comfort studies, attributed in part to *RayMan*'s ease of use software [13] and also because uses a combination of climatic and personal variables as clothing and activity. PET's outcomes give a clear indication on the comfort temperature because it is still in degrees and therefore logical for people that are no experts in meteorology [14]. However, it is essential to note that this index is adapted to European reality and may not necessarily represent the real feeling of other areas users comfort. Several studies demonstrated this fact [12,15,16].

Researches as developed by Lin [16] shows that thermal adaptation, which involves physiological, psychological and behavioural factors, also plays an important role in assessment by users thermal environments. Study conducted in Taiwan, which has a hot and humid climate, examines outdoor thermal comfort and confirms thermal adaptation existence using PET index [16]. The formulae development to evaluate thermal comfort applicable to each local climate as well as multiplicity of thermal comfort predictive indices hinders both urban planning models application and studies results comparison. Thus, PET index was selected for its wide applicability in this research area [12].

To understand human thermal perception, more surveys in several contexts are necessary to understand regional particularities [17,18] and then to suggest some recommendations for improving urban planning by taking into account thermal comfort in tropical climates [18]. This study assumes as premises that urban layouts have an effect on local climatic conditions, that adequate ventilation for hot and humid climates is critical for mitigating thermal discomfort and that local planning is an important instrument to regulate urban structure. The ventilation aimed at pedestrian's thermal comfort covers different aspects, pointing to the need for a multidisciplinary approach to the matter. This study aimed to evaluate ventilation's effect on pedestrian's thermal comfort in hot and humid coastal regions through an integrated analytical approach of urban layouts, thermal perception and urban legislation.

2. Methodology

To achieve research's objective, an Integrated Method for Ventilation Analysis was developed. This method uses a multidisciplinary approach to evaluate urban ventilation, the study focus. Bearing in mind the adopted procedures, ventilation is analysed under three spheres: objective, subjective and legislative. The objective sphere is considered using urban typology analysis effect over the wind. In the subjective sphere, pedestrians' thermal comfort is analysed by wind's caused sensation. Finally, the legislative sphere considers how ventilation is addressed in the Urban Master Plan.

For the Integrated Method for Ventilation's Assessment, it was initially defined a sampling area in the city of Vitória, Espírito Santo's capital (Brazil), that presents different land occupation forms for wind behaviour pretended evaluation. In the sequence there are presented the main climate characteristics of Vitória, the measurement points identification and the urban legislation aspects that interfere in the analysis process.

2.1. Climate background

According to the Köppen-Geiger climate classification, Vitória's climate is humid tropical and is included in group A, i.e., hot and humid [19]. The tropical climate of low latitude regions, Vitória's case, features small temperature variations during the day. In addition, two seasons predominate, summer and winter, and the rainy season is not well defined with higher rainfall in the summer and a high relative humidity [20].

In Vitória, high temperatures are recorded in summer, and mild temperatures are recorded in winter. According to the National Institute of Meteorology (INMET) the city had an average summer temperature of approximately 27 °C while in winter was 22.8 °C, and in fall and spring were 24.3 °C and 24.7 °C, respectively [21]. Temperature has a 3.5 °C average daily range being highest temperatures recorded in noon period (10 h–16 h). Recorded average minimum temperature was 21.8 °C, and average maximum temperature was 29.1 °C, with an average relative humidity of 77%.

Wind speed is higher during spring and summer and lower during autumn and winter. In June, average wind speed was 3.11 m/s, year's lowest, while a value of 4.28 m/s was recorded in November, corresponding to the period (2000–2013) highest average speed.

2.2. Measurement protocol

Empirical analysis adopted method based on a climate sample covering eleven points arranged over two lines perpendicular to the waterfront. The goal was to cover different situations allowing a better understanding of urban typology effect on wind speed and direction (Fig. 1).

Measurement days criteria were defined by the ability to represent their season, therefore, were selected days with little cloudiness, with no rainfall and minimum wind speed of 5 m/s selected. These criteria aimed a better perception of wind and its changes by the instrument's sensor at a height of 110 cm, considering that the desired evaluation would be more evident during the type of days selected than on days with lower wind speeds.

Climate data collected at noon in winter and at 11 a.m. during spring and summer to ensure temporal similarity, keeping in mind daylight, savings time discrepancies. The afternoon period selected measurements for being thermal comfort issues most critical, because of highest daily temperatures. Time selection followed two criteria: amount of people on streets and solar path.

At selected time, which corresponded to lunch break, had the greatest number of people on streets observed. This was a very important factor concerning the increase in pedestrian's number for questionnaires application. The selected time was also the greatest solar height period, thus preventing buildings from forming shadows and from affecting visible sky area over sampling points, given that the buildings have different heights.

Microclimatic measurements from all eleven points performed using four portable mini weather stations located at each point. Stations were positioned at 110 cm from the ground (at abdomen height), following ISO 7726 [22] guidance, which rules measurements for physical quantities standards. Despite the variable wind be the focus of research, the mini-stations were used to obtain necessary data to calculate PET index. One digital portable hygro-thermo-anemometer, one datalogger, one globe thermometer, one windsock, one tripod and one weather shelter (Table 1) composed each mini weather station.

Thermal sensation data were obtained through questionnaire with pedestrians at each sampling points. The questionnaires aim

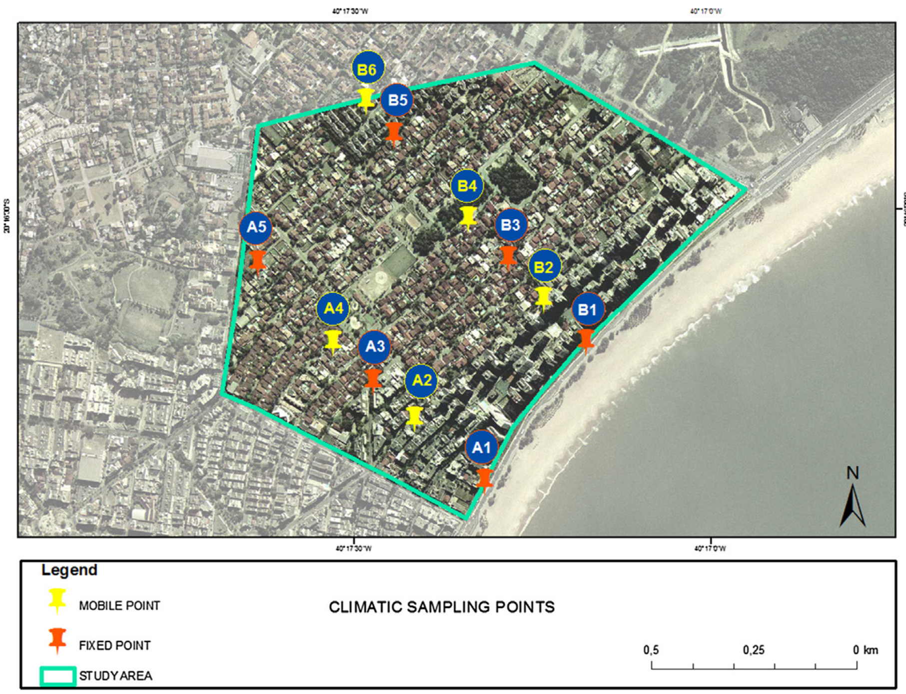

Fig. 1. Delimitation of the study area and definition of sampling points (map drawn in *ArcGIS* software, version 10.2, 2013 with a *Google Earth* satellite image, 2013).

Table 1
Description of the instruments used in the microclimatic measurements.

Description of the instruments			
Item	Description	Quantity	Accuracy
01	Hygro-thermo-anemometer, model ITAN 7000, brand: Instrutemp	04	±(2% read + 0.2 m/s); ±(2% read + 40 fpm); ±0.5 °C; ±0.9 °F; ±4%UR
02	Hobo Data logger, model: U12, brand: Onset	04	±0.35 °C; ±2.5%
03	Grey globe thermometer made with official table tennis ball painted in grey ($e^1 = 0.9$) and thermal sensor model TMC20-HD, brand name: Onset	04	±0.21 °C
04	Windsock made with TNT fabric	04	–
05	Adjustable tripod, model: W7370, brand: V7	04	–
06	Weather shelter: fabricated using PVC and cardboard	04	–

Note: e^1 = emissivity.

to analysis the effect of the microclimatic variables on pedestrian's thermal comfort. ISO 10551 [23] guidance based the questionnaire, which rules on the assessment of thermal environment influence using subjective judgement scales. Therefore, the questionnaire was structured in three parts: 1. log data, 2. individual data and 3. thermal sensation and preferences votes. Log data refers to location, time and date of interview. Individual data gathers information about gender, age, weight, height, activity that the pedestrian was performing before the interview and their clothing. The votes on thermal sensation and preferences were obtained from questions that evaluated three scales of subjective judgement, which were also based upon ISO 10551 [23], namely, a perception scale, rating scale and a preference scale.

For thermal perception votes, Fanger's seven-point scale was used [24], following ISO 7730 [25]. This scale was selected because it is more objective than the PET nine-point scale and because while testing the method, it was observed that climatic conditions do not vary largely in Vitória city. Therefore, pedestrians do not identify a wide range of thermal sensations, making seven-point scale more suitable for this study.

Equation (1) was used for calculating the sample size [26], considering the population of Vitória city to be 348,268 inhabitants [27] and a 5% sampling error. As a result, 400 inhabitants was the minimum sample size.

$$n = \frac{N \times (1/E^2)}{N + (1/E^2)} \quad (1)$$

where n = sample size, N = population size and E = sampling error.

Microclimatic measurements and interviews were conducted simultaneously at all points. A total of 841 questionnaires were used, where 51% interviewed were female. The respondents exhibited a mean age of 36 years, a normal body mass index (BMI) considered, and a metabolic rate of 102.5 W/m^2, which corresponds to mild activity; the clothing worn thermal insulation was of 0.5 clo, corresponding to a pair of jeans and a short-sleeved shirt (Table 2).

Each campaign reflects measurements performed on two subsequent days at eleven sampling points. It must be emphasised that three campaigns were performed during each year's season, according to the climate characteristics of Vitória municipality, to wit, winter (cooler season), spring (intermediate season) and summer (hottest season).

The sampling days were organised by sections. On one day, the data were gathered from points belonging to Section A, and on the next day, from points in Section B. The sampling consisted of obtaining climate data through measurements made the same time as pedestrians answered questionnaires.

To simultaneously obtain climate data and conduct questionnaires, mini weather stations were positioned on pre-defined fixed

Table 2
Personal data of the respondents during the three measurement campaigns.

Personal data of the respondents	Age	Weight (kg)	Height (m)	BMI	Met. rate (W/m²)	I (clo)
N	841	841	841	841	841	841
Mean	36	69.4	1.68	24.4	102.5	0.5
Median	33	67.0	1.70	24.1	110	0.4
Standard deviation	13	13.1	0.09	3.9	33.4	0.3
Coeff. variation	0.37	0.19	0.05	0.16	0.33	0.51
Minimum	17	45.0	1.45	17.1	58	0.3
Maximum	65	105	1.90	35.1	200	1.1
Range	48	60	0.45	18	142	0.9

Caption: BMI: body mass index (weight/height^2); Met. rate: metabolic rate; I: thermal insulation; N: sample.
Note 1: The percentage of people was calculated as a function of the female gender.
Note 2: The means, medians, and all remaining parameters were calculated based on the number (N) of questionnaires applied in the sampled section and period.
Note 3: BMI values; BMI ≤ 20 = underweight; $20 < \text{BMI} \leq 25$ = normal weight; BMI >25 = overweight.

and mobile points. For Section A, the mini weather stations were positioned at fixed points A1, A3 and A5, and the mobile points station switched from A2 to A4. For Section B, the mini weather stations were positioned at fixed points B1, B3 and B5, and the mini weather station in mobile points switched from B2 to B4 and then to B6.

The mini weather station positioned on a mobile point remained there for a period of twenty five minutes. In Section A, stations fixed points remained for ninety minutes at each location; and in Section B, stations remained for two hours (Table 3). The time a station remained at each point was defined in accordance with the results obtained by applying the initial method as well as the period the mobile point station remained in, plus the time required for its displacement between each section points.

The data was recorded at intervals of three minutes; this information was compared with data from the official weather station located at the airport [28]. The airport values was use as base of measurement day's climatic conditions. Mobile stations data collected were statistically treated to correct time delay relative to fixed stations data. Thus, linear regression analysis was performed for each mobile station individually data; were then correlated with data from fixed stations for each sector and measurement day.

2.3. System for assessing the suitability of the Urban Master Plan

To assess Vitória's Urban Master Plan [29] suitability on urban ventilation issues, a legal device analysing system was proposed. The methodological procedures developed to create the system were explained and published by Silva and Alvarez [30]. Data collected from microclimatic measurements and questionnaires were then added to the system.

Based on literature review and microclimatic measurements, framework for Urban Master Plan evaluating concerning urban natural ventilation was structured. To use the system, guidelines were established, and the parameters required for its application were selected based on theoretical framework and empirical phase of this study.

A minimum percentage by the charts proposed use (subsection 3.4) was established for the Master Plan to be considered as suitable regarding analysis' focus. To achieve this percentage, a minimum score was required for urban porosity (setback areas and occupancy rate) items related, identified in measurements and in theoretical review as having the greatest impact on natural ventilation. The main strategy for achieving the results was to assign different weights for each item (see subsection 3.4). A higher value was given to those items in Master Plans that interfere more with wind flow and intensity, as the coefficient of utilisation, occupancy rate and setback areas that showed the most significant for the promotion of ventilation.

Next, the system was applied to a sampling area to illustrate its use and to examine instruments concerning urban ventilation in Vitória's Master Plan. To illustrate the method, urban sectors selected as area of analysis were neighbourhoods of *Mata da Praia* and *Jardim da Penha*, identified by Urban Master Plan as ZOC3 (Controlled Occupation Zone) and ZOR/09 (Restricted Occupation Zone).

3. Results and discussion

The Integrated Method permitted a multidisciplinary analysis of ventilation for pedestrian thermal comfort. The obtained data supported the development of four aspects: a) an assessment of urban typology effect in ventilation, b) a scale of wind perception and preference, c) PET thermal range calibration and d) a system for Master Plan evaluation, whose results will be presented and discussed below.

3.1. Assessing the effect of urban typology in ventilation

To analyse the results obtained by the measurements, the use of parametric tests (comparison between means) was selected because in a preliminary analysis of the data, the means proved to be more representative of the climatic conditions of each sampling

Table 3
Measurements schedule.

Measurement schedule of climate data						
Season	Sector A			Sector B		
Winter	**Points**[b]	**Start**	**End**	**Points**	**Start**	**End**
	Fixed (1; 3; 5)	12 h	13 h30 min.	Fixed (1; 3; 5)	12 h	14 h
	Mobile 2	12 h	12 h25 min.	Mobile 2	12 h	12 h25 min.
	Mobile 4	13 h05 min.	13 h30 min.	Mobile 4	12 h40 min.	13 h05 min.
	–	–	–	Mobile 6	13 h35 min.	14 h
Spring[a]/Summer[a]	**Points**	**Start**	**End**	**Points**	**Start**	**End**
	Fixed (1; 3; 5)	11 h	12 h30 min.	Fixed (1; 3; 5)	11 h	13 h
	Mobile 2	11 h	11 h25 min.	Mobile 2	11 h	11 h25 min.
	Mobile 4	12 h05 min.	12 h30 min.	Mobile 4	11 h40 min.	12 h05 min.
	–	–	–	Mobile 6	12 h35 min.	13 h

For the fixed points was made individual files for each period corresponding the mobile points.
Notes:
[a] Time fixed in summer time function.
[b] Fixed e Mobile points location.

point. This observation was particularly true with respect to wind speed; because this parameter fluctuates considerably, the maximum and minimum values mask the more frequent conditions, and thus, the means are more representative.

For Sector A, the wind flow gradually decreases as it moves away from the sea (Fig. 2a–c). Such a reduction is more evident in the winter campaign, when the wind reaches the buildings perpendicularly.

Despite typology low porosity in Sector A blocks and the high density of sea closest block, an avenue perpendicular to the seashore allows southwest wind to be channelled to points A2 and A3 (Figs. 3 and 4). In addition, distribution of roads parallel to the shore allows northeast wind channelling.

Just as occurred in Sector A, in Sector B, the effect of typology on the ventilation flow was also more evident during the winter campaign (southwest/southeast wind). However, the behaviour of the wind in this section did not occur gradually as in A because of the different urban typologies observed in this sector (Fig. 5a–c).

In Sector B, a pattern in wind speed data was identified. Greatest speeds were always recorded at point B1, and smallest at point B4. Between points B1 and B2, the smallest difference in wind speed values was recorded. The reason for these results is *Mata da Praia* neighbourhood typology; while this neighbourhood has tall buildings, these buildings are at large distances from each other, thus permitting a good wind flow between blocks (Fig. 6).

In both sectors, the maximum wind speeds were always recorded at the points located closer to the sea – A1 and B1 – in the southeast/southwest direction (sea-land) as well as in the northeast direction (crosswind) due to the lack of obstacles formed by urban typology in those directions. In the southwest direction, there were no constructions in front of the sampling point, and in the northeast direction, there was an avenue parallel to the seashore that serves as a venting channel.

With respect to point B4, the wind encounters obstacles because of urban squares shape and high tree density (which are very close to each other), interfering with wind continuous flow coming from northeast quadrant (Fig. 7). The prevailing winds in Vitória's region are those from northeast quadrant. The road orientation network parallel to this quadrant enables wind to flow through streets, especially in Sector B, located closer to neighbourhood edge, adjacent to a large open area airport associated.

An analysis of both Sectors points reveals that points A4 and B4 are located near city squares. However, distinct square shapes and vegetation arrangement patterns affect northeast wind distribution in different ways. While in A4, the square with sparse vegetation directs wind into the sampling point inside, in B4, dense vegetation is an obstacle to northeast wind. Between points A1 and A2, a wind reduction greater than that between B1 and B2 is observed. In Sector A, there is a great urban density and reduced distance between buildings, while in Sector B, these distances are larger.

The results of the three measurement campaigns (winter, spring and summer) enabled the identification of interference from different types of topologies in the natural ventilation flow. The values recorded for wind speed at the eleven points confirm the hypothesis that distinct urban typologies affect the natural ventilation flow in various ways. The behaviour of the wind in Section A and B exhibits a pattern that was repeated in all the seasons. Wind speed gradient changes based on urban roughness [3], i.e., higher building heights result in lower wind speeds at pedestrian level. Nevertheless, wind speed at pedestrian level depends on a combination of factors, as can be inferred from measurements results.

In the study area, specifically at point B2 located behind the tallest buildings (sixteen floors) but with large distances between buildings, wind speed smallest reduction was recorded. This finding confirms that even though buildings represent considerable obstacles, they do not interfere at the pedestrian level depending on the distance that separates them. Conversely, most relevant reductions in wind speed values were recorded at measured points between houses (two floors) but with small distance between them. These results indicate that at pedestrian level, distance between buildings as a function of their height is key for wind to be able to flow between blocks.

Presence of large-sized vegetation in urban areas is often considered fundamental to thermal comfort, especially aiding to reduce temperature [5,6]. In this sense, it is worth paying attention to the importance of distribution and type of vegetation because both density and orientation interfere with wind passage [7]. Next to point B4, dense vegetation arrangement pattern forms obstacles for wind circulation, while next to A4, vegetation arrangement pattern, consisting of sparse trees and palm trees, better preserves ventilation.

3.2. Scales of wind perception and preference

The assesment method integrated approach for ventilation allowed pedestrian's perception and preference for ventilation to be defined at each sampling point. This capability was achieved through questionnaire specific questions application. Each respondents was asked how he or she perceived the wind at that time, with these possible answers: strong, well-ventilated, stable or weak wind. Afterwards, the respondent was asked if he or she would like the wind to be weaker, stronger, or the way it was at that moment.

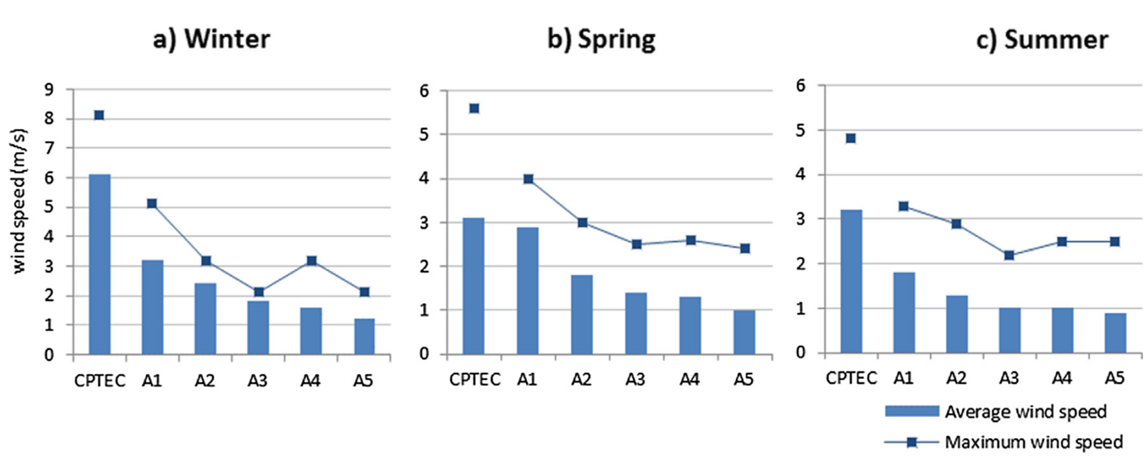

Fig. 2. Behaviour of the wind in Sector A: a) in winter, b) in spring and c) in summer.

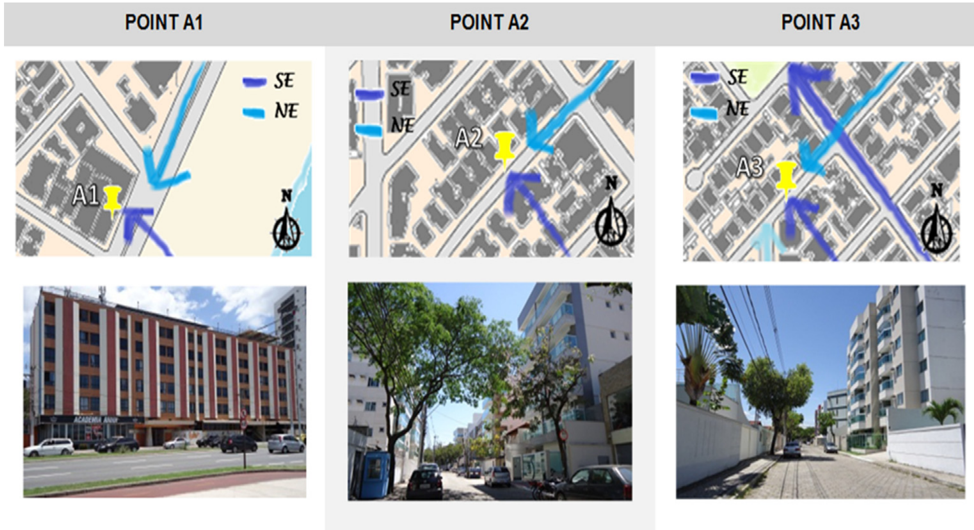

Fig. 3. Wind direction and urban typology of Sector A: points A1, A2, A3.

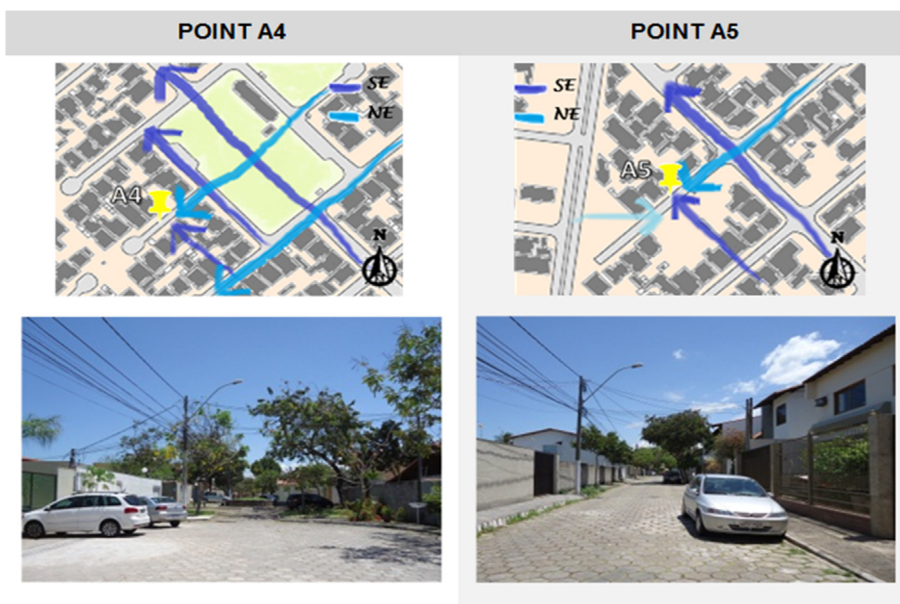

Fig. 4. Wind direction and urban typology of Sector A: points A4, A5.

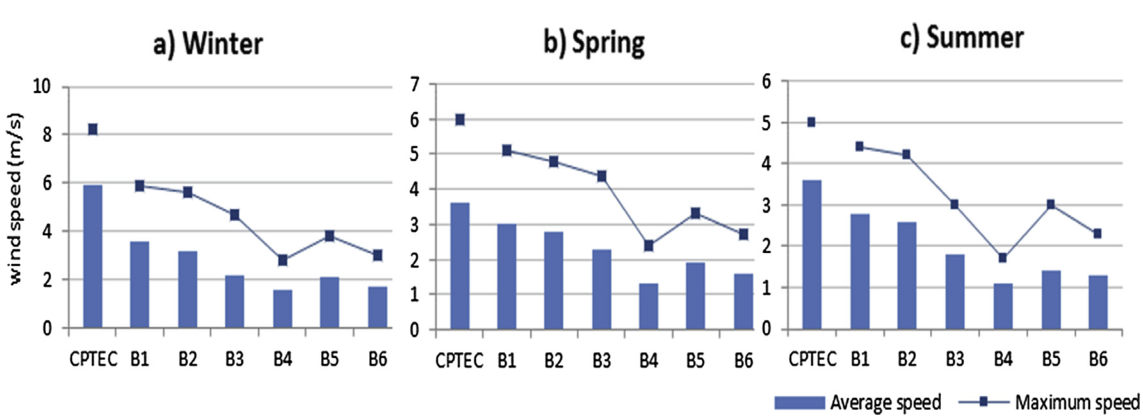

Fig. 5. Behaviour of the wind in Sector B: a) in winter, b) in spring and c) in summer.

Fig. 6. Wind direction and urban typology of Sector B: points B1, B2, B3.

During winter campaign in both sectors, for sampling points closest to the sea, a higher number of respondents perceived wind as very strong. Percentage data were defined based on sampling point's average. At sampling points A1 and A2, the majority of people perceived wind to be strong (60%) and would prefer it to be weaker (66%). At sampling points A3 and A4, the majority of respondents perceived the area to be well ventilated (61%) and would keep wind as it was (57%). At point A5, result indicated a preference for maintaining wind condition as it was at that moment (50%), and a significant percentage of respondents preferred wind to be stronger (42%).

In section B, points B1, B2, and B3 were perceived as having strong wind (84%), and respondents preferred it to be weaker (70%). Points B4, B5 and B6 were perceived as being well ventilated (65%), and the preference was for maintaining conditions at that moment (67%).

Results synthesis obtained in survey applied to pedestrians in winter is presented in Fig. 8a–d plots.

Spring campaigns indicated higher air temperatures and a slightly slower wind speed than winter (the previous) campaign. Moreover, wind perception and preference at each point differed from winter campaign, as illustrated in Fig. 9a–d summary plots.

During spring in Sector A, only point A1 was perceived as having strong wind (67%), and the preference was for it to be weaker (53%). Points A2 and A3 were considered as being well ventilated (54%), and the preference was to maintain the conditions at that moment (65%). Despite point A4 also being considered as well ventilated by majority of respondents (52%), there were numerous responses indicating a preference for stronger winds (52%), even though in A4, average wind speed (1.3 m/s) was only slightly slower than in A3 (1.4 m/s). However, in A4, temperature recorded was higher (32 °C), which clearly indicates that under higher temperatures, people prefer stronger winds. Point A5 was perceived as having a stable wind condition (65%), and preference was for stronger winds (70%).

During spring in Section B, similarly to in winter, points B1, B2, and B3 were perceived as having very strong wind (70%); however, there was a preference for weaker winds (72%) only in B1. In B2 and B3, the preference was to maintain that moment conditions (64%).

Fig. 7. Wind direction and urban typology of Sector B: points B4, B5, B6.

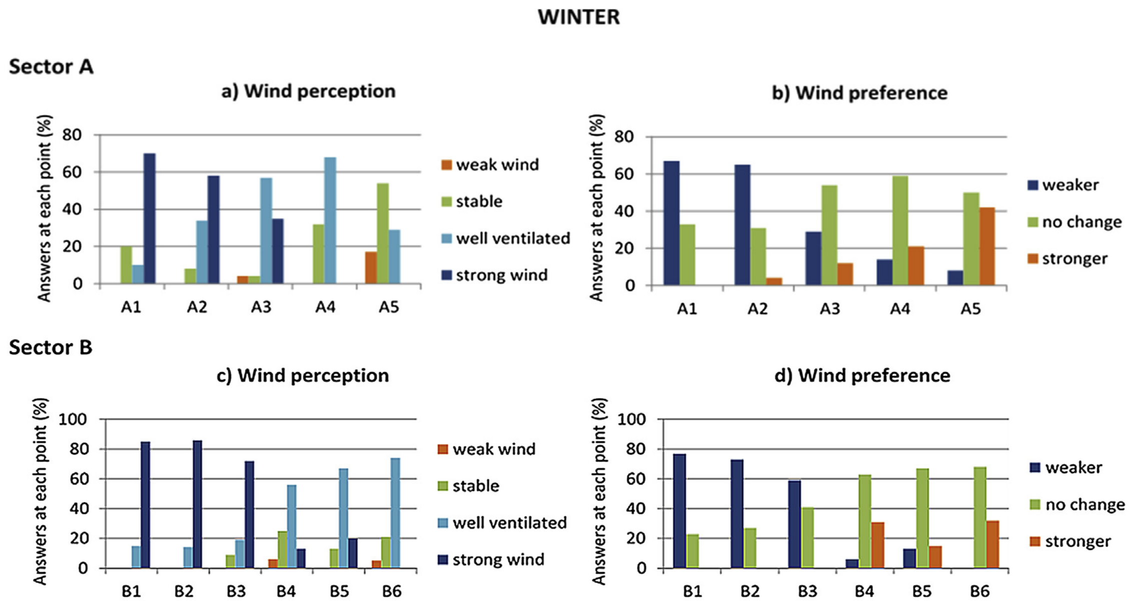

Fig. 8. Wind perception and preference in the winter campaign: a) and b) Sector A; c) and d) Sector B.

These results confirm the finding that under higher temperature conditions, people prefer stronger winds.

During summer campaigns, the three stations highest temperatures and lowest wind speeds were recorded (Fig. 5). Wind's perception as being strong was only observed at points B1 and B2 (72%), and points A1 and B3 were identified as being well ventilated (61%).

During summer campaigns, the majority of respondents perceived wind as being weak and preferred it to be stronger, except for points A1, B1, B2 and B3. At these points, on previous campaigns, wind was considered very strong, and the majority preferred wind to be weaker. During summer, largest preference for maintaining the conditions at that moment was observed, as indicated in Fig. 10a–d summary plots.

A preference for higher wind speeds during moments of higher air temperatures was identified. Wind speed data combined with wind perception responses and preference obtained in questionnaires were tabulated by absolute frequency of responses. The aim was to establish wind speed ranges based on wind perception and preference (Fig. 11).

Plots analysis in Fig. 7 allowed ventilation ranges for each of the three seasons to be defined, as listed in Table 4. During winter, there is a greater acceptance of wind ranges between 0.9 m/s and 2.4 m/s. In spring, upper limit of this range speed increases to 2.9 m/s. In summer – with higher temperatures – a preference for stronger winds was detected, and at the same time, perception of wind intensity also changed.

After wind perception and preference ranges identification, a scale of ventilation perception was established as a variation's function in mean temperature recorded during the three measurement campaigns (Table 5).

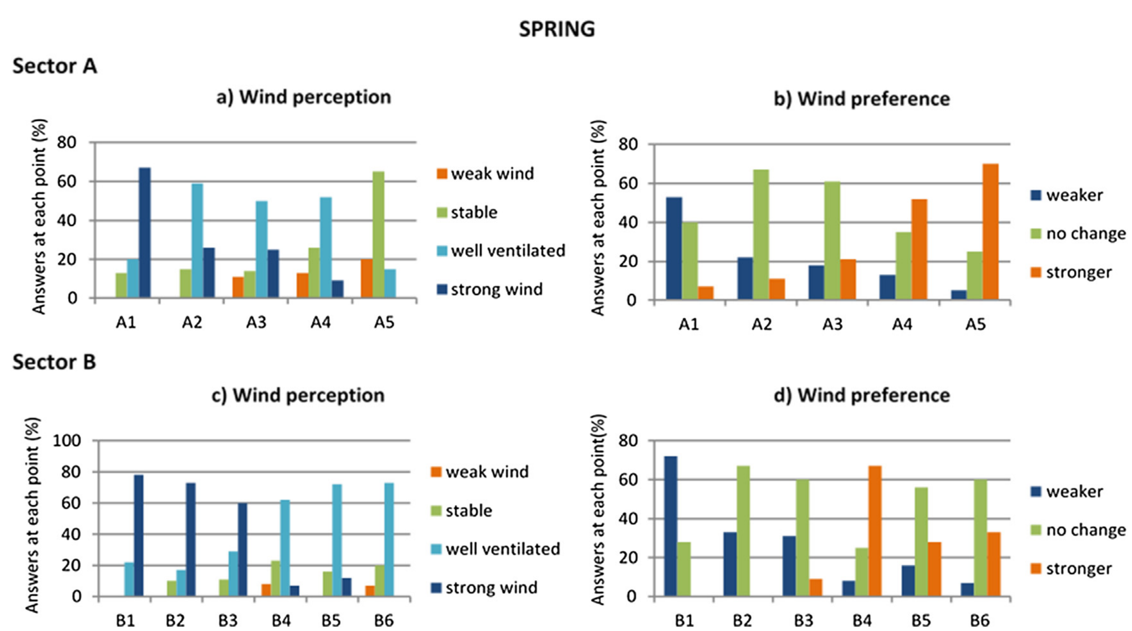

Fig. 9. Wind perception and preference in the spring campaign: a) and b) Sector A; c) and d) Sector B.

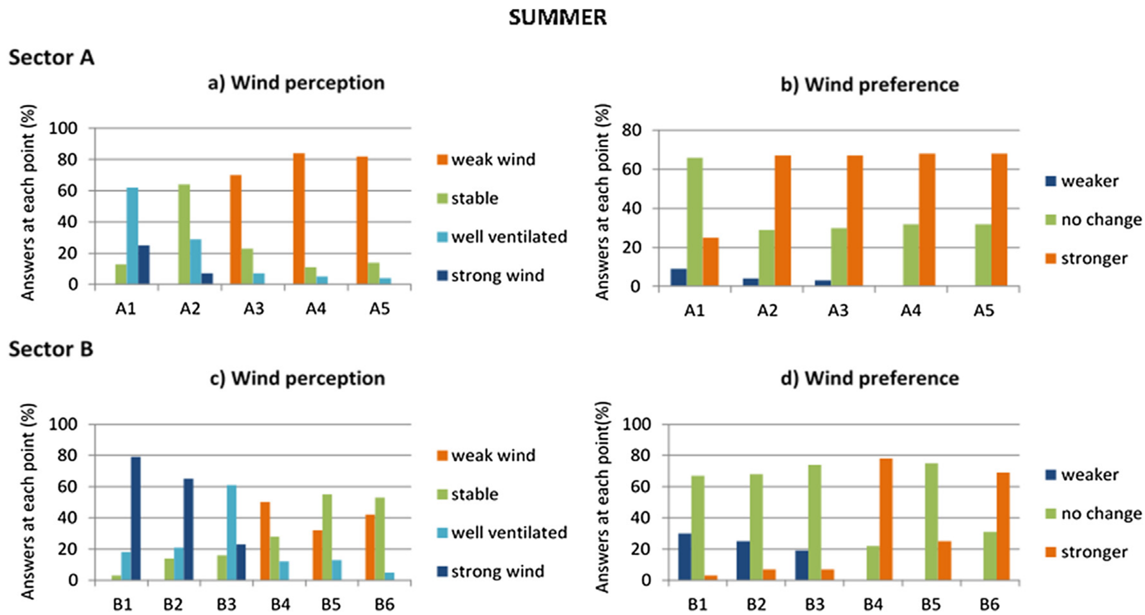

Fig. 10. Wind perception and preference in the summer campaign: a) and b) Sector A; c) and d) Sector B.

3.3. Calibration of PET's thermal range

Studies such as those performed in Refs. [12,15,16] have concluded that local calibration models must be developed to define an index that is capable of adequately predicting thermal comfort. In 46% of Johansson's et al. [12] analysed research, calibration was used to estimated levels of comfort with subjective responses (votes), reaching a setting of comfort zones for regional use. Use of a comfort index which tracks thermal adjustable facilitate its utilization in urban planning. Thus, a calibration of PET's thermal range was proposed for Vitória city.

Population sample, previously characterised in item 2.2, consisted of 51% female respondents, a mean age of 36 years, normal weight, a metabolic rate of 102.5 W/m^2, which corresponds to mild activity, and thermal insulation of clothing of 0.5 clo, which corresponds to wearing a pair of jeans and a short-sleeved shirt.

After organising respondents personal data, PET index value was calculated using *RayMan 1.2* software for each of the 841 respondents. Values obtained were then cross-referenced with responses given in thermal perception questionnaires.

Using these results, a table of frequency was prepared to indicate the relative frequency of thermal sensation responses as a PET's thermal range function (Fig. 12). For measurement days, a predominance of responses indicating thermal neutrality (neutral) sensation followed by warmth (hot) sensation was observed.

From frequency plot analysis, thermal sensation ranges were defined based on PET range observed during measurement days, which ranged from 18 °C (winter) to 46 °C (summer). In this

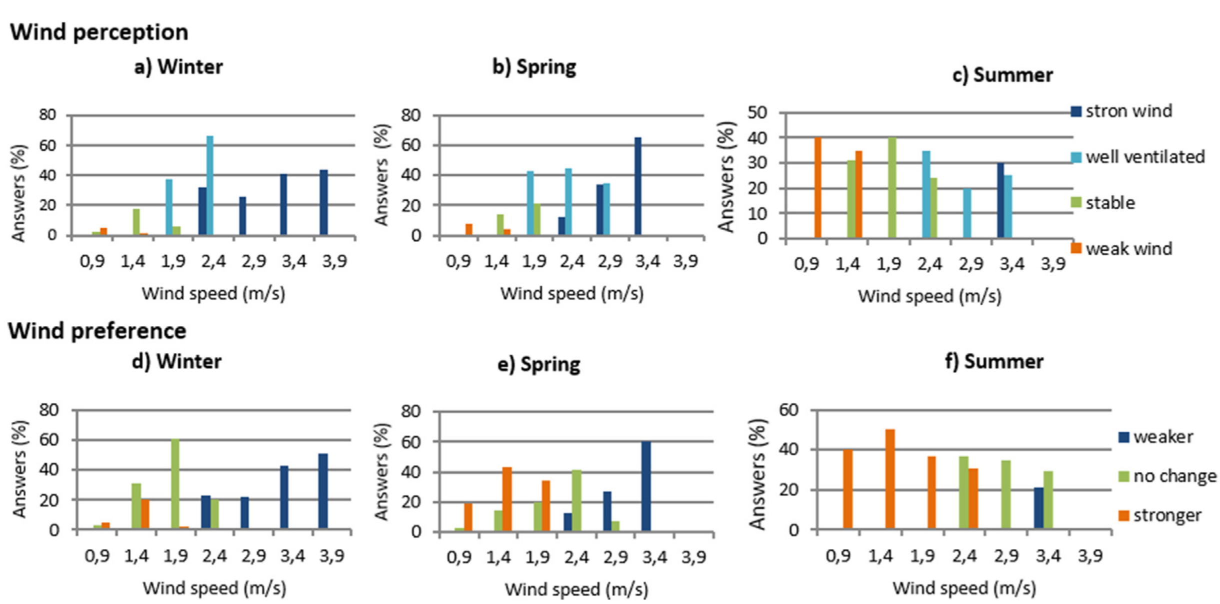

Fig. 11. Wind perception and preference as a function of mean wind speed: Wind perception in a) winter, b) spring and c) summer and wind preference in d) winter, e) spring, and f) summer.

Table 4
Scale of wind perception and preference.

Wind velocity range (m/s)	Perception	Preference
Winter (22.9 °C–28 °C)		
≤0.9 m/s	Weak wind	Stronger
0.9 m/s < wind ≤ 1.9 m/s	Stable	No change
1.9 m/s < wind ≤ 2.4 m/s	Well ventilated	No change
>2.4 m/s	Strong wind	Weaker
Spring (29 °C–33.1 °C)		
≤0.9 m/s	Weak wind	Stronger
0.9 m/s < wind ≤ 1.9 m/s	Stable	No change
1.9 m/s < wind ≤ 2.9 m/s	Well ventilated	No change
>2.9 m/s	Strong wind	Weaker
Summer (35.2 °C–37.2 °C)		
≤1.4 m/s	Weak wind	Stronger
1.4 m/s < wind ≤ 2.4 m/s	Stable	No change
2.4 m/s < wind ≤ 3.4 m/s	Well ventilated	No change
wind > 3.4 m/s	Strong wind	Weaker

Table 5
Scale of wind perception.

Wind perception for the three seasons			
Perception	Wind range (m/s)		
	22.9 °C–28 °C	29 °C–33.1 °C	35.2 °C–37.2 °C
Weak wind	≤0.9 m/s	≤0.9 m/s	≤1.4 m/s
Stable	0.9 m/s < wind ≤ 1.9 m/s	0.9 m/s < wind ≤ 1.9 m/s	1.4 m/s < wind ≤ 2.4 m/s
Well ventilated	1.9 m/s < wind ≤ 2.4 m/s	1.9 m/s < wind ≤ 2.9 m/s	2.4 m/s < wind ≤ 3.4 m/s
Strong wind	>2.4 m/s	>2.9 m/s	wind > 3.4 m/s

manner, PET (Table 6) was calibrated for Vitória city based on seven-point scale proposed by ISO 7730 [25] answers.

To evaluate thermal range calibration for Vitória, new measurements were performed at different points of the city and adjacent municipalities on days with different climatic conditions. Over 800 interviews were conducted, and simultaneously, several climatic variables (temperature, humidity, airspeed and radiant temperature) were recorded. PET index was calculated tor each of the respondents using the *RayMan* software. Values obtained using PET index were matched to Vitória's range. Subsequently, these values were compared with questionnaires obtained answers. Interviews accuracy rate was 93%, indicating that the calibrated range is suitable for the city and, more broadly, that the calibration method is suitable for this purpose.

Lin's [16] results analysis shows that when compared with European's scale (18–23 °C PET) [31] thermal acceptable range, the thermal acceptable range in Taiwan was much higher (21.3–28.5 °C PET) [16], indicating that people in different regions have different thermal requirements. In agreement with Taiwan's [16] study results, PET values for Vitória were higher, especially because of thermal adaptation [12,15,16] caused by regional acclimatization.

3.4. Urban Master Plan assessment system

Proposed system was structured based on a summary chart (Fig. 13), where it was indicated whether the item was included in Urban Master Plan. Then, achieved score was added to column weight column: if the item were included in the Master Plan, it would receive whole score; otherwise, adopted value would be zero. To increase system's objectivity, situations with numerical scaling potential were not included, it means that the item only have two possibilities for score, if is included on the Master Plan receives whole score, if is not included receives zero.

For Master Plan to be considered appropriate, a minimum margin of 60% of the total value was established. This value needed to be obtained in each urban zone delimited in Master Plan. For Plan to reach minimum value, it must have contained at least the items that ensured urban porosity layout, such as occupancy rate and setbacks.

To be able to convert these items into urban control indices with maximum and minimum values defined on Plan, in-depth studies are necessary to adjust different climatic contexts values. For each urban zone, appropriate values should be defined based on its topographic location and its positioning relative to prevailing winds as well as surrounding urban layout effect. Urban Master Plan assessment system test was performed on two urban zones of *Mata da Praia* neighbourhood in Vitória: ZOC3 and ZOR/09 (Fig. 14).

System accordance, ZOC3 area was considered satisfactory with a score of 80%. This area had significant results regarding issues of setback and occupancy rate and scored in all items

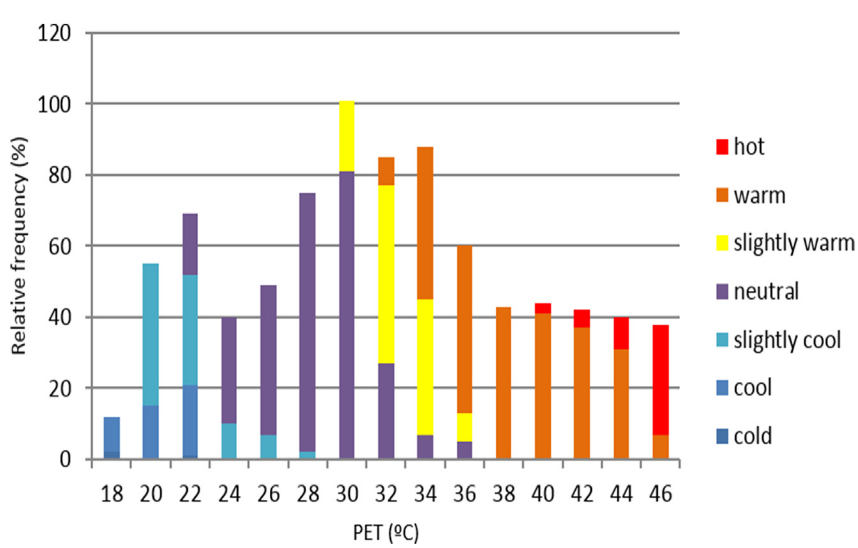

Fig. 12. Relative frequency of thermal sensation occurrence as a function of the PET index.

Table 6
PET intervals for Vitória.

Thermal sensation	PET for Europe Matzarakis and Mayer [31]	PET for Vitória
Very cold	≤4 °C	–
Cold	4 °C < PET ≤ 8 °C	18 °C < PET ≤ 20 °C
Cool	8 °C < PET ≤ 13 °C	–
Slightly cool	13 °C < PET ≤ 18 °C	20 °C < PET ≤ 22 °C
Neutral	18 °C < PET ≤ 23 °C	22 °C < PET ≤ 30 °C
Slightly warm	23 °C < PET ≤ 29 °C	30 °C < PET ≤ 34 °C
Warm	29 °C < PET ≤ 35 °C	–
Hot	35 °C < PET ≤ 41 °C	34 °C < PET ≤ 46 °C
Very hot	>41 °C	>46 °C

related to these two variables. Results obtained by the system's application in that area confirmed measurement phase findings. Distances between buildings were observed to contribute to a good wind flow between blocks, which confirms that the proposed system is suitable to evaluate Master Plan concerning ventilation issues.

In ZOR/09 area, Plan did not reach minimum score and was thus not considered satisfactory despite area's adequate maximum occupancy rate and low buildings. Results indicate that absence of side and rear setbacks obstructs ventilation. In Vitória's Master Plan, as in ZOR/09 urban control table of contents, in most zones, buildings are allowed to ignore side and rear setbacks up to second floor. This exemption represents an inconvenience to urban ventilation because wind speed is lower on first floor, creating greatest need for front, side and rear setbacks precisely at this level.

The absence of setbacks, whether on first floor or other floors, has significant consequences for the city because these setbacks hinder wind flow between blocks. Especially in a seaside town such as Vitória, it is crucial to allow and encourage maritime ventilation flow to areas located within the city. According to guidelines established for using the assessment system, Master Plan must achieve a score of at least 60% in each zone to be considered suitable to issues concerning ventilation. Hence, it can be concluded that Vitória's Master Plan is not suitable regarding this aspect.

	EVALUATION CHART				
	ITEM TO BE ANALYSED	YES	NO	SPECIFICITIES	WEIGHT
1	The coefficient of utilisation and the maximum number of floors are defined in a way that to achieve the highest score in both indices, reducing the maximum occupancy rate allowed is required				15%
2	The maximum occupancy rate is less than or equal to 60%				15%
3	Provides mechanisms of tax reduction if the occupancy rate is 20% less than the maximum allowed per zone (example: exemption from payment of the building permit tribute)				5%
4	Establishes minimum value for front setback				5%
5	Establishes a minimum value for front setback on the first three floors (including the semi-basement)				10%
6	Establishes a minimum value for side setback				5%
7	Establishes a minimum value for side setback on the first three floors (including the semi-basement)				10%
8	Establishes a minimum value for rear setback				5%
9	Establishes a minimum value for rear setback on the first three floors (including the semi-basement)				5%
10	Determines the maintenance of roads that serve as ventilation channels				10%
11	The routes are scaled according to the density rate of blocks parallel to these routes				5%
12	Identifies the preservation/promotion of open spaces				5%
13	Provides and/or promotes the planting of large-sized vegetation				5%
				Total value	

OBSERVATIONS:

1. Item 1: The definition of the maximum coefficient of utilisation is not required if the maximum number of floors is defined and the maximum occupancy rate is less than 60%.
2. Item 3 may be considered appropriate when the maximum occupancy rate is less than 40%.
3. Items 4, 6 and 8: These items should not be analysed when the maximum number of floors is 3 (three) or less. In this case, the values assigned to these items should be redistributed to items 1 and 2. Hence, the weight of item 1 becomes 20%, and the weight of item 2 becomes 25%.
4. Item 12: The evaluation of adequacy refers to the maintenance of open spaces in the radius of influence of the neighbourhood and not of the zone. To analyse this item, the urban zoning map should be considered. The open spaces in the Master Plan can be classified as environmental protection zones, and the proposed framework does not apply to them.
5. Item 13: To analyse these items, it is important to identify whether criteria for the arrangement of large-sized vegetation exist, such that the vegetation does not form a dense mass blocking the wind.

Fig. 13. System for evaluating the Urban Master Plan concerning ventilation (figure adapted from Ref. [26]).

Fig. 14. Urban zoning of the *Mata da Praia* neighbourhood/ES (figure adapted from Ref. [26]).

Wind speed decreases as it approaches ground [4], and greatest reductions occurred in areas located behind buildings with short distances between them. Consequently, ventilation was most reduced precisely at pedestrian level. Still, Vitória's Master Plan in different zones allows buildings to occupy the first three floors whole lot. This aspect conflicts with achieving urban thermal comfort, especially because ventilation in a hot humid climate is crucial to accelerate heat exchanges and ensure comfort.

4. Conclusions

The importance of using an integrated approach to evaluate urban ventilation with the aim of pedestrians' thermal comfort should be emphasised. To really understand how ventilation affects thermal comfort in a given location, this phenomenon must be investigated on objective, subjective and legislative levels. This study identified some fundamental aspects to define public policies related to urban planning of a city in these domains. For example, the importance of examining how urban typologies affect wind flow, how this flow interferes with pedestrians' thermal comfort and how legislative sphere addresses this issue in Master Plan were all highlighted.

Urban typology roughness decreases wind speed as it approaches ground. At pedestrian level, urban porosity was identified as the most influential urban characteristic on ventilation because this porosity permits wind circulation between blocks. According to study results, tall buildings (sixteen floors) with a large distance between them have less of an effect on wind speed than houses (up to two floors) with a small distance between them.

Thermal range considered comfortable varies for each climate reality, which occurs due to the populations' ability to adapt to different thermal contexts. Thus, it is evident that comfort perception depends not only on climatic conditions but also on individual subjective and psychological factors. As identified in Lin [16] the population in hot and humid climates feel a neutrality sense in higher PET temperatures, was identified an increase of 5.5 °C PET on considered neutral temperature. In Vitória's research was pointed an increase of 7 °C PET relative to the thermal range identified by Matzarakis and Mayer [31]. Values obtained in both researches shown PET's applicability for different regions, paying attention to the temperature range calibration. Therefore, PET proposed calibration, validated later under various circumstances, demonstrates the method's potential for this purpose.

Considering that wind speed is slower at pedestrian level compared with higher locations, it is imperative that urban control legislation establish a level of setback on all floors. This establishment would allow for efficient ventilation levels, which would help mitigate local thermal discomfort. Thus, it is reiterated that only with local reality study it is possible to adopt public policies planning/urban planning integrated with local weather elements understanding, regionally appropriate. Consequently, it is possible to increase this subject knowledge using a multidisciplinary approach, which can be translated into practices aimed at improving thermal comfort at each locality.

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