Adaptive Thermal Comfort for Buildings in Portugal based on Occupants' Thermal Perception

MATIAS L.[1], ALMEIDA S.[2], PINA SANTOS C.[1], REBELO M.[1], CORREIA GUEDES, M.[3]

[1]Laboratório Nacional de Engenharia Civil - LNEC (National Laboratory for Civil Engineering), Lisbon, Portugal
[2] Fundação para a Ciência e Tecnologia - FCT (Foundation for Science and Technology), Lisbon, Portugal
[3] Instituto Superior Técnico - IST (Higher Technical Institute), Lisbon, Portugal

ABSTRACT: Three years ago, LNEC initiated an interdisciplinary research study intended to develop an adaptive approach with a view to defining the indoor thermal comfort requirements applicable to Portuguese buildings. Extensive field surveys (285) have been carried out on office and educational buildings, both conventional and special (elderly homes) residential buildings. Field surveys assessed and measured the main indoor environmental parameters during summer, winter and mid-season, and, simultaneously, the occupants' perspective was evaluated through questionnaire. This paper proposes and justifies an adaptive thermal comfort variable (*Comf*) consisting of thermal sensation and thermal preference. Considering this new variable, a linear regression (R^2=0.85), between the corresponding temperature (*Tcomf*) and the outside temperature, was presented, as well as the thermal comfort range for the different analysed population samples.
Keywords: Thermal comfort, occupants' perception, adaptive model

INTRODUCTION

Energy consumption, comfort and indoor living space quality have gained increased significance with the approval (2001) of the European Directive "Energy Performance of Buildings". Thus, new energy efficient and passive building concepts and technologies recommend a revision of comfort standards.

The existing conventional thermal comfort standards, which are largely responsible for the use of air conditioning (AC), are based on complex equations resulting from laboratory research, relating human comfort with individual parameters and the surrounding physical thermal environment. However, a significant set of data resulting from field research are available today, which suggests that conventional standards are too rigid and neglect fundamental aspects of the process of thermal comfort achievement, such as the human ability - and necessity - to exercise adaptation.

Alternative comfort criteria have been proposed by various researchers, who have developed models based on the so-called adaptive theory of thermal comfort. This theory considers that the achievement of thermal comfort is a dynamic process, in which humans interact both physically and psychologically with the environment, i.e. by adapting the environment to their needs and by adapting themselves to the environment.

This type of models has been developed using the results of field studies carried out on a large number of buildings, mainly office buildings, in several countries all over the world. The implementation of adaptive criteria is naturally dependent on contextual factors, like climate, social and cultural habits, expectations, as well as on regional or country specific building solutions.

Nowadays, adaptive models have began to be included in thermal comfort standards. In ASHRAE thermal comfort standard (ASHRAE 55) [1], an adaptive model was adopted as an optional method for determining acceptable thermal conditions in naturally conditioned spaces. In a recent European Standard (EN 15251[2]), the acceptable "summer" indoor temperatures (cooling season) for buildings without mechanical cooling systems are based on a model derived from the results of a European Project [3].

In the last few years, Portugal has been experiencing a clear changing trend towards the installation and use of air conditioning systems, either in service or in residential buildings. On the one hand, the great majority of new service buildings are equipped with mechanical air conditioning systems, either due to commercial reasons, productivity, or due to high internal thermal loads (artificial lighting, equipment), and solar gains through windows. Nevertheless, a large percentage of (older) existing service buildings are still naturally ventilated.

On the other hand, in dwellings, increasingly more inadequate construction solutions have been adopted, which disregard the climate conditions, the location and the orientation of buildings, almost imposing the use of mechanical systems.

Current Portuguese thermal and energy regulations define rigid indoor conventional (reference) comfort conditions (heating season: 20 ºC; cooling season: 25 ºC).

Hence, the implementation of adaptive comfort criteria could contribute to a more rational and sustainable approach to building design and operation, which might lead thus to reducing the use of air conditioning and to ultimately increasing the occupants' comfort perception.

In Portugal, only a limited number of research studies were carried out on a small number of buildings, invariably office buildings [3, 4].

Therefore, a few years ago, the National Laboratory for Civil Engineering (LNEC) initiated an interdisciplinary research study in this field. The main purpose of this study is to develop an adaptive approach aimed at defining the indoor thermal comfort requirements applicable to Portuguese buildings, on the basis of extensive field surveys carried out on occupied buildings.

This paper includes the results of the analysis to the occupants' thermal perception and expectation, by relating them to both measured and collected indoor thermal environments and outdoor climate.

In particular, the relation between the occupants' thermal sensation and preference was analysed for different types of activities, throughout different seasons. By identifying the influence of the outdoor conditions on the occupants' thermal environment perceptions, a more detailed analysis was done, by taking into account the thermal sensation/preference and the outside temperature.

Results obtained in this study show that occupants may tolerate (under wider comfort conditions) broader temperature ranges than those indicated in current standards, in particular in the heating season.

As a final remark, the interdisciplinary team of this research study - involving physicists, social scientists, and civil engineers - has contributed to a deeper understanding and to a better modelling of adaptive thermal strategies, considering the typical Portuguese moderate (Mediterranean) climate, traditional and changing ways of living, designing and operating buildings.

FIELD SURVEYS

This field research is focused on the assessment, in real use conditions, of indoor environments and of the response of the occupants of office and educational buildings, as well as of conventional and special (elderly homes) residential buildings.

The cases studied included both air conditioned (mechanical heating/cooling systems) and naturally ventilated buildings (NV). Most NV buildings had passive features and technologies (great adaptive possibility); and a few of the AC buildings were equipped with automated control systems (almost null adaptive potential).

Between July 2006 and May 2008, extensive field surveys (285) have been carried out on forty buildings, all over the country, and an important set of responses (2367) was obtained from a sample of 1518 individuals.

Field surveys assessed and measured the indoor environmental parameters, namely air temperature (*Ta*), operative temperature (*Top*), air speed (*va*) and relative humidity (*RH*), during summer, winter and mid-season. Local outdoor climatic conditions (air temperature, *Tout*, and relative humidity, *RHout*) were based on data from the National Meteorological Institute. All measurements were performed using sensors and probes, in compliance with thermal comfort standard specifications [5], and the field studies can be classified as Class I[1] [6].

Occupants' perspective was assessed through a questionnaire specifically designed for this research program with the support of researchers from the Social Ecology Division [7] of LNEC.

The questionnaire included the aspects as follows: identification of both individual and technological adaptive opportunities, as well as of the easiness and degree of satisfaction in implementing them; evaluation of psychosocial factors like the participants' perceptions and expectations as regards their thermal environment; contribution to characterise and evaluate the influence of the factors that determine human thermal perception.

Therefore, subjective opinion scales were defined, which enabled responders to give their opinion on their perception and expectation (sensation, preference, tolerance, evaluation) regarding their thermal environment.

Table 1 presents two subjective scales used in the questionnaire, respectively, thermal sensation, *tsi*, and thermal preference, *tpi*, as refers to the thermal occupants' perception considered in this paper.

Table 1: Thermal sensation and preference scales

Thermal sensation (*tsi*)		Thermal preference (*tpi*)	
- 3	Cold	- 3	Much cooler
- 2	Cool	- 2	Cooler
- 1	Slightly cool	- 1	Slightly cooler
0	***Neither cool nor warm***	***0***	***As it is***
+ 1	Slightly warm	+ 1	Slightly warmer
+ 2	Warm	+ 2	Warmer
+ 3	Hot	+ 3	Much warmer

1 - Despite the fact that only one height measurement was performed.

RESULTS AND ANALYSIS

In order to understand how the thermal comfort can be expressed and how it relates to the environmental parameters and psychosocial factors, an analysis was performed on the results obtained, either from measurements of environmental parameters or from questionnaires [8, 9]. Figure 1 presents the indoor thermal environment conditions (operative temperature) and the corresponding outdoor conditions (running mean temperature) achieved as a function of the season of the year. Figure 2 presents the individual thermal sensation votes, *tsi*, (Table 1) for all participants.

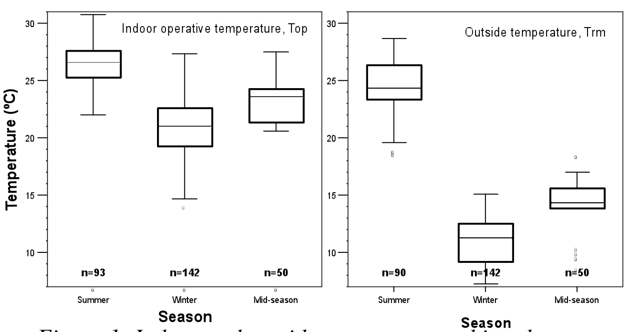

Figure 1: Indoor and outside temperature achieved in field surveys

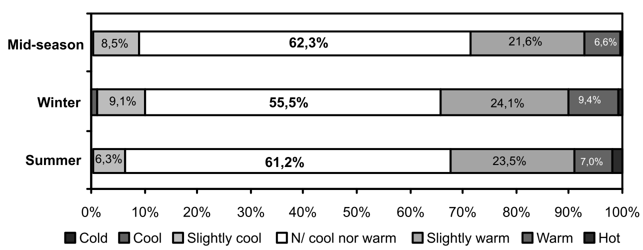

Figure 2: Thermal sensation votes, tsi

From the previous figures, we can see that at least 88 % of participants (Fig. 2) voted *tsi* = 0 or *tsi* = ± 1 (Table 1), despite the indoor temperatures achieved, above 25 ºC in summer and below 20 ºC in winter, for more than 50 % of the surveys performed (Fig. 1). This fact indicates that the reference limits defined in the national regulations (conventional model) are not representative of the thermal comfort conditions in Portugal, which stresses the need for more flexibility in the definition of these conditions.

Another analysis performed considering the occupants' thermal perception, through the cross-tabulation between *tsi* and *tpi* votes and the measured temperatures, makes it possible to draw the following main inferences:

- Outdoor climatic conditions influence thermal preference, because, although being in a *neutral* situation (*tsi* = 0), a significant percentage of users (20%) would rather feel *slightly cold* (*tpi* = -1), in summer, and *slightly warm* (*tpi* = +1) in winter;
- On the other hand, considering the users that prefer maintaining the conditions *as they are* (*tpi* = 0), the result seems to indicate that these users would rather have a *neutral* environment (*tsi* = 0) in summer, whereas in winter the option lies between a *neutral* and a *slightly warm* environment (*tsi* = 0 or 1).

Both these illations and the results from several other field surveys performed all over the world [4, 6, 7] confirm the strong influence of the external climatic conditions on the occupants' thermal perception, either expressed as thermal sensation (*tsi*), as thermal preference (*tpi*), or as another related variable.

Thermal sensation / Thermal preference

Considering the mean thermal sensation[2] (*Mts*) and the mean thermal preference[2] (*Mtp*), for each field survey, a statistical linear regression was performed, between *Mts* and the indoor operative temperature (*Top*) and *Mtp* / *Top,* with high correlation coefficients (namely $R^2 = 0.67$ and $R^2 = 0.91$).

Assuming that when *Mts* or *Mtp* are null, the corresponding indoor temperatures indicate, respectively, the neutral temperature, *Tn*, and the preference temperature, *Tp*.

Table 2 presents the neutral and the preference temperatures achieved considering all field data by season.

Table 2: Neutral and preference mean temperatures

Temperature	Summer	Winter	Mid-season
Neutral	24.8	19.3	21.9
Preference	24.0	21.4	22.9

Unlike the conclusions from other important studies [3, 6], the present field study shows significant differences between the two calculated temperatures, *Tn* and *Tp*, mainly in the heating season (winter).

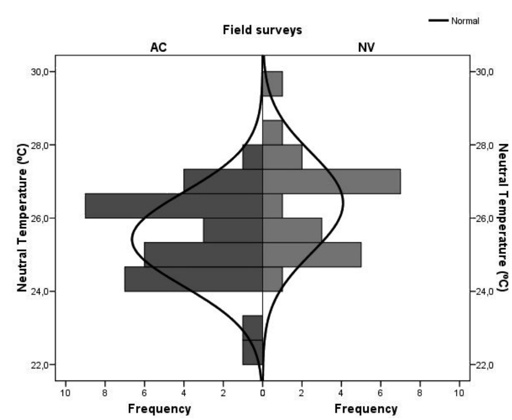

Figure 3: Neutral temperatures for AC and NV buildings European adaptive thermal comfort model (EN 15251)

---

[2] - Corresponding to the average of the individual thermal sensation (*tsi)* or preference (*tpi)* votes (Table 1).

Figure 3 presents the distribution of the neutral temperature achieved in summer for buildings with (AC) and without mechanical cooling systems (NV).

Occupants of rooms without AC (NV) show a higher thermal tolerance, probably due to the greater adaptive opportunities and the different thermal expectations.

The adaptive model adopted in the European standard [2] is based on the linear relation between neutral temperatures and outside temperature, *Trm*.

In order to test the European adaptive model on these field survey results, Figure 4 shows the acceptable temperature limits defined in the standard, for a normal expectancy level [2] and ensuring that 90 % of occupants are satisfied.

Figure 4 presents the neutral temperature data regarding NV spaces (in office buildings, elderly homes and educational buildings).

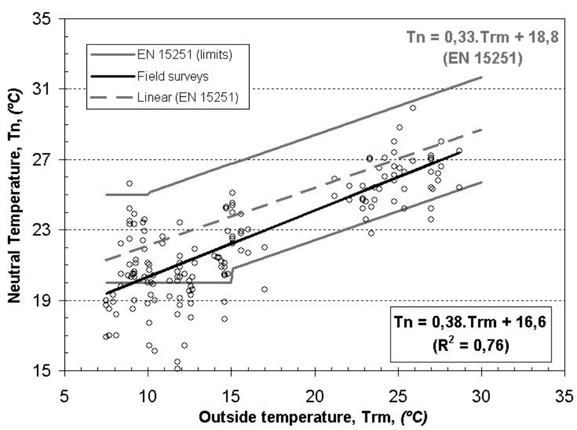

Figure 4: Field surveys neutral temperatures and temperature limits according to EN 15251

Comparatively with the European standard limits [2], Figure 4 denotes (lower outside temperature) a significant set of data beyond the comfort range, mainly because the results reveal a linear relationship between neutral and outside temperatures (in all the range) and not a "kink" point like in EN 15251 relationship curve.

By assuming that the temperatures, at which discomfort will not be unduly intrusive, are up to ± 3 ºC [2] above or below the estimated neutral temperature (field surveys), the upper limit temperature for *Trm*= 25 ºC is 1 ºC less than the EN 15251 limit value. However, for an outside temperature of 10 ºC the difference is more significant (3º C).

Proposed thermal comfort variable (Comf)

We have seen that thermal sensation and thermal preference are strongly correlated. Indeed, the individuals' thermal sensation and preference can mutually influence each other.

The difference between neutral and preference temperatures (Table 2) shows that thermal comfort cannot be explained by thermal sensation alone, as many authors propose, or just by thermal preference. A significant fraction of responders declared to be neutral, although preferring slightly colder or warmer temperatures. Can we assume that these individuals are comfortable? Can we say that thermal comfort is a more complex and dynamic process involving both sensation and preference? We believe so.

By basing our work on such assumptions, a new variable was defined based on thermal sensation and thermal preference, leading to four distinct profiles of thermal comfort (*Comf*).

Table 3: Profiles of Thermal Comfort (Comf)

Comf	tsi	tpi	N
Discomfort	≠ 0	≠ 0	416
↓	= 0	≠ 0	219
	≠ 0	= 0	224
Comfort	= 0	= 0	656

In order to understand whether these profiles were distinct among them, as refers to other aspects related to thermal perception of individuals, such as, mean thermal tolerance, *Mtt*, or mean thermal environment evaluation, *Mte*, one-Way ANOVA tests were performed.

Significant differences were found between some of the groups regarding their *Mtt* (F (2.1515) = 61.880; p <0.05) and their *Mte* (F (3.1514) = 276.650; p <0.05).

Individuals representing the ideal type of thermal discomfort (*tsi* ≠ 0; *tpi* ≠ 0) consider themselves as the least thermally tolerant (p<0.05). Although the other groups reveal a statistically equal *Mtt* (p>0.05), a descriptive analysis of Figure 5 shows a slightly higher *Mtt* in the two last groups of respondents. These groups are represented by those who prefer the thermal environment "*as it is"* (*tpi* = 0), whether they have a neutral thermal sensation or not (*tsi* = 0 and *tsi* ≠ 0).

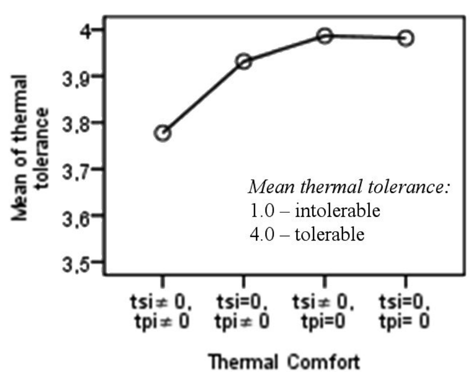

Figure 5: Mean thermal tolerance, according to thermal comfort profiles

In the same way, *Mte* (Fig. 6) is more favourable among the groups that prefer the thermal environment "*as it is*" (*tpi* = 0), regardless of their thermal sensation, revealing a strong link between thermal comfort and preference.

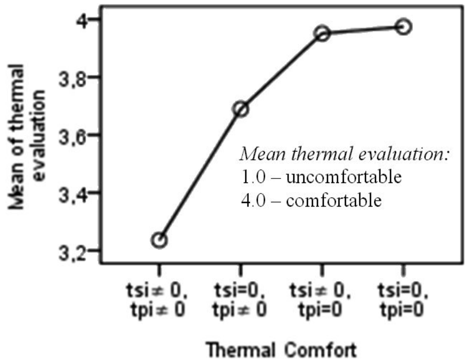

Figure 6: Mean evaluation of the indoor thermal environment, according to thermal comfort profiles

Considering that thermal comfort can be expressed by this new variable (*Comf*), we tried to understand what could influence this state. For the purpose, multiple linear regression analyses were performed, which made it possible to predict the dependent variable behaviour (*Comf*). Figure 7 shows the complexity of relationships between several variables, which contributes, either directly or indirectly, to explain the thermal comfort variability.

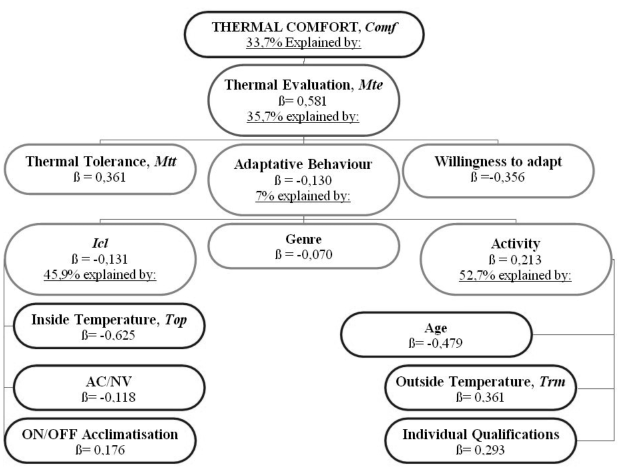

Figure 7: Explanatory model of thermal comfort[3] (Comf)

People's thermal evaluation of indoor environment (*Mte*) is correlated with the perception of thermal comfort (R = 0.58) and justifies, in average, the 33.7 % in *Comf'* variation. This shows that a more favourable *Mte* corresponds to an increased perception of thermal comfort.

3 - ß values correspond to standardised partial regression coefficients and represent the relative importance of each independent variable (measured in distinct units) in the explanation of the dependent variable [10].

On the other hand, we noticed that a more favourable *Mte* is, in turn, linked to high levels of thermal tolerance and to a small number of adaptive measures, as well as to a residual interest in acting on the thermal environment. This demonstrates that the individuals considering the thermal environment as comfortable do not reveal the need to act on it.

The adaptive behaviour, measured by the number of actions (drinking cold or warm fluids, changing clothes, opening windows, etc…) on indoor environment, is explained only by 7 %. This result can be due to its complex nature and to the diversity of situations that promoted it, as well as to the fact that few individuals have acted so as to adapt themselves to the environment. Also, the high percentage of positive ratings in the thermal environment assessment can account for this result.

Nevertheless, it was detected that a greater occurrence of adaptive measures is linked to a lower clothing rate (ß = -0,131) and to a higher activity rate (ß = 0,213). Furthermore, it was observed that women act more than men on the environment.

Variation in individuals' clothing is almost half explained by variables closely related to indoor environment characteristics, meaning that the lower the indoor temperature is, the higher the clothing index will be. The acclimatisation system (AC/NV) and its state (ON/OFF) are also associated with a clothing rate. Moreover, the activity index is more related to the responders' profile: the older and less educated responders have less activity levels.

Thermal comfort (Tcomf) / Outside temperature

Considering the proposed thermal comfort variable (*Comf*) introduced and justified above, a thermal comfort temperature, *Tcomf*, was developed. This temperature corresponds to indoor temperatures when *tsi* and *tpi* are null (Table 3). Figure 8 represents the linear regression between *Tcomf*[4], and the outside temperature, *Trm*.

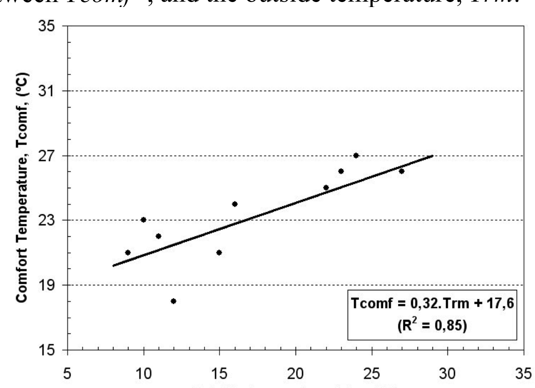

Figure 8: Thermal Comfort temperature (Tcomf) as a function of outside temperature

4 - Binned values of comfort temperature for each degree of outside temperature.

This linear relation, similarly to standard adaptive models [1][2], makes it possible to estimate thermal comfort conditions based on outside temperature.

Figure 9 shows the distribution of thermal comfort temperature, *Tcomf*, achieved in the present field study for the distinct occupational profiles of buildings, (office buildings, elderly homes and educational buildings), where the different temperature tolerances are obvious, being higher for the older population (elderly homes).

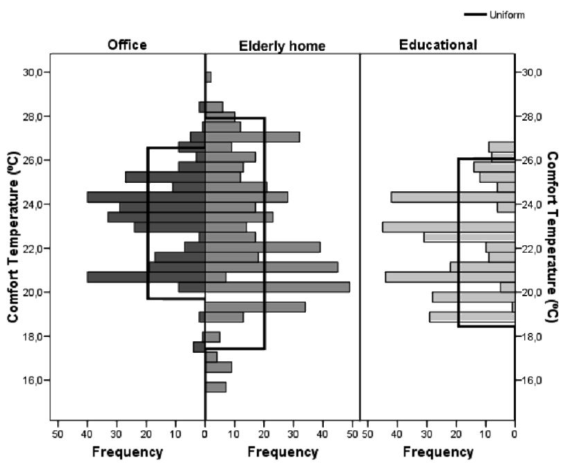

Figure 9: Thermal comfort temperatures (Tcomf) for different occupational profiles

SUMMARY AND CONCLUSIONS

This research study is focused on assessing, in real use conditions, indoor environments and the response of occupants of office and educational buildings, as well as of special residential buildings (elderly homes).

The analysis of the results obtained from the extensive field surveys (285), carried out on several buildings (40), and the set of questionnaires (2367) completed by the responders, make it possible to draw the following main conclusions:

- Clearly the occupants' perception votes show that they tolerate temperatures beyond rigid indoor conventional (reference) comfort conditions;
- The outside temperature has strong influence on the occupants' thermal perception, either expressed as thermal sensation (*tsi*), as thermal preference (*tpi*), or as another related variable.
- The present field study shows significant differences between the neutral temperature, *Tn*, and the preference temperature, *Tp*, mainly in the heating season (winter).
- A new variable (*Comf*) has been defined considering what people feel (*tsi*) and what they prefer (*tpi*), allowing the creation of different profiles of individual thermal perception.
- Statistical analysis reveals the multiplicity of physical and also psychosocial factors that play a role in the definition of thermal comfort processes and conditions, revealing the complexity of this phenomenon.

However, a more detailed analysis of results is currently under way, in order to improve this adaptive approach with a view to defining the indoor thermal comfort requirements applicable to Portuguese buildings.

ACKNOWLEDGEMENTS. The present research work is partially funded by FCT, within the scope of the Project PTDC/ECM/71914/2006 - Development of Sustainable Visual and Thermal Comfort Models.

REFERENCES

1. ASHRAE (2004), ANSI/ASHRAE Standard 55-2004: Thermal Environmental Conditions for Human Occupancy. Ed. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta.
2. CEN (2007) European Standard EN 15251: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. Brussels, European Committee for Standardization.
3. McCartney, K., Nicol, F. (2002) Developing an adaptive control algorithm for Europe. *Energy and Buildings*, 34: p. 623-635.
4. Guedes, M. Correia (2000) Thermal Comfort and Passive Cooling Design in Southern European Offices, *PhD Thesis*, The Martin Centre for Architectural and Urban Studies, Cambridge University, Cambridge.
5. CEN (2001) European Standard EN ISO 7726: Ergonomics of the thermal environment. Instruments for measuring physical quantities (ISO 7726:1998). Brussels, European Committee for Standardization.
6. de Dear, R.; Bragger, G.; Cooper, D. (1997) Developing an Adaptive Model of Thermal Comfort and Preference. *Final Report ASHRAE RP-884*.
7. Matias, L.; Santos, C.; Guedes, M. Correia (2006) Condições de conforto térmico em edifícios em Portugal. Modelo adaptativo. In *National Symposium Encontro Nacional Sobre Qualidade e Inovação na Construção – QIC2006*, Lisbon, Portugal, November 21-24: p. 355-365.
8. Matias, L.; Santos, C.; Rebelo, M.; Silva, D.; Guedes, M. Correia (2007) Constant or variable indoor environments? Sustainable option of adaptive thermal comfort. In International Congress *Portugal SB07 – Sustainable Construction. Materials and Practices, Challenge of the Industry for the New Millenium*. Lisbon, Portugal, September 12-14: p. 403-410.
9. Guedes, M. Correia; Matias L. (2008) Thermal Comfort in Services' Buildings: A study in Portugal. In *World Renewable Energy Congress X and Exhibition (WREC)*, Glasgow, Scotland, July 19-25.
10. Johnson, Richard A.; Wichern, Dean W. (1992) Applied multivariate statistical analysis. Englewood Cliffs: Prentice-Hall.