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ELECTRICITY CONSUMPTION ANALYSIS & ENERGY EFFICIENCY
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Final ELECON Workshop

Federal Institute of Santa Catarina - IFSC, Florianópolis, Brazil, September 12-14, 2016.

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Abstract

Thermal comfort is a subjective concept, which describes a person's state of mind in terms of whether he/she feels hot or cold. The thermal comfort feeling is influenced by environmental and personal factors. Its most commonly used indicator is the air temperature, which, alone, is not a valid indicator of thermal stress. Thermal comfort should be measured by the number of people complaining of thermal discomfort. There are several procedures to assess the thermal comfort, but they require the measurement of many variables. This paper aims to propose a procedure to assess the thermal comfort. This proposal includes the creation of a ratio scale and a set of statistical procedures to treat the data gathered from this scale. This procedure was used to evaluate the influence of fans in the thermal comfort feeling of the occupants of a small office, and it proved to be useful. This procedure makes easier the inclusion of the human in the control loop of the comfort systems.

Keywords: Ceiling fans, Energy efficiency, Thermal sensation, Thermal comfort.

1. Introduction

According to Health and Safety Executive (HSE) [1] the term 'thermal comfort' describes a person's state of mind in terms of whether he/she feels too hot or too cold. Environmental factors, such as humidity and sources of heat, wind, etc., combine with personal factors, such as clothing and work-related factors to influence the thermal comfort feeling [1]. The interaction of these factors makes the term thermal comfort difficult to define.

Also according to Health and Safety Executive [1], the most commonly used indicator of thermal comfort is air temperature – it is easy to use and most people can relate to it. However, air temperature alone is not a valid or accurate indicator of thermal comfort or thermal stress. It should always be considered in relation to the other environmental and personal factors. Then, thermal comfort is not measured by room temperature, but by the number of people complaining of thermal discomfort, thus, the best one can hope to achieve in thermal comfort is a thermal environment that satisfies the majority of people sharing it [1].

HSE [1] makes a good deal explaining why the room temperature alone is not a valid indicator of thermal comfort, rather it should be considered along with environmental and personal factors. The environmental factors are: air temperature, which is the temperature of the air surrounding the body; radiant temperature due to the heat that radiates from warm objects. This is the case when there are heat sources in the considered environment. Air temperature is greatly influenced by radiant temperature; air velocity, the speed of air moving across the people; humidity, the amount of water vapour in the air, high humidity

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environments prevent the evaporation of sweat from the skin. High humidity can be a problem in hot environments, because the evaporation of sweat is the main method of heat reduction [1].

Among the personal factors HSE [1] highlights Clothing insulation and metabolic heat. Thermal comfort is very much affected by the insulating effect of clothing. Wearing too much clothing may be a primary cause of heat stress even if the environment is not considered warm or hot. On the other hand, if clothing does not provide enough insulation, the person may be at risk from cold injuries [1].

HSE [1] asseverates that the impact of metabolic rate on thermal comfort is critical. The physical characteristics of a person, such as weight, age, fitness level and gender, should be considered when dealing with thermal comfort [1].

Because the state of thermal comfort felt by a person is a subjective concept, once it is in close connection with person's physical and mental condition [2, 3], involving several factors as mentioned above, it is difficult to translate a person's physical and mental wellbeing into numbers. ASHARE has created a scale ranging from -3 to +3, which captures the person's thermal feeling (-3: cold, -2: cool, -1: slightly cool, 0 neutral, 1: slightly warm, 2: warm, 3: hot) [3].

According to [2], different indices, combining the ASHARE scale and the personal and environmental factors, have been proposed over the years, among them the PMV (Predicted Mean Vote) [2, 4] and the associated PPD (Predicted Percentage of Dissatisfied) [4] may be cited.

Although these indices improve the assessment of the thermal feeling, they require the measurement of several quantities, what can be time consuming or sometimes impossible to do. Then, because the human being is the best sensor for thermal comfort feeling, this paper aims to present a method to assess the people's thermal comfort without using any kind of measurement, just by interviewing them. This research have been carried out at the cluster habitat in G2Elab, Grenoble, France.

Since the proposed method does not requires extensive measurements, it will simplify the design of several experiments in order to assess the effect of several factors on thermal comfort feeling, facilitating, in such a way, the inclusion of the human in the control loop of the comfort systems.

The proposed method can be used to assess the thermal comfort feeling of the occupants of an office, and this is important because the Heating, Ventilation and Air Conditioning (HVAC) comfort systems temperature setup can be adjusted according to the human's comfort feeling and not only according to the room temperature.

Residential and commercial buildings represent about 30% to 40% of the electricity consumption of the power grids. HVAC systems account for 39% of the energy consumed in commercial buildings [5-9]. Then, HVAC system optimization plays an important role in energy-efficient buildings design.

2. The thermal comfort scale

According to ASHARAE, the comfort feeling can be assessed by means of a scale ranging from -3 (cold) to +3 (hot) [3]. This paper proposes a linear rating scale ranging from -10 (very cold) to +10 (very hot) as illustrated in Fig. 1, which is an extension of the ASHARAE. Such an extension provides the respondents with more degrees of freedom to express his/her thermal feeling.

The scale presented in Fig. 1 is quite simple. The respondents are invited to draw a line on the scale mark that best represents their thermal feeling. It is worth mentioning that the neutral mark (N) of the scale corresponds to the absolute thermal comfort.

The scale presented in Fig. 1 can be easily converted into a software application with a slider. In fact, the version presented in Fig. 1 was used only in the first experiments, after that it was quickly converted into a software and hosted in the computer server of the G2Elab where the experiments have been carried out.

During the experiments, from time to time, this scale appeared on the screen of all the work stations of the cluster habitat and the respondents should drag a slider handle to indicate their thermal feeling.

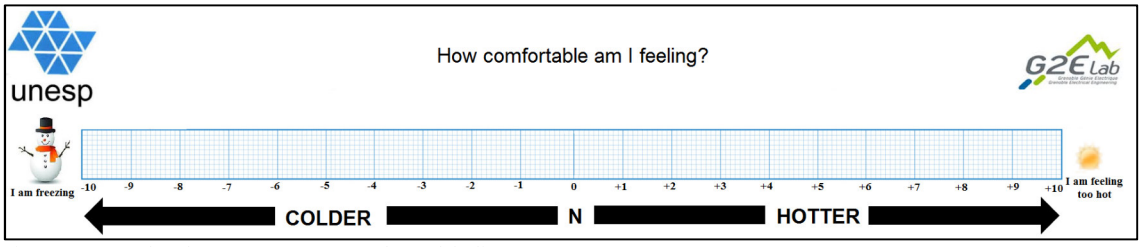


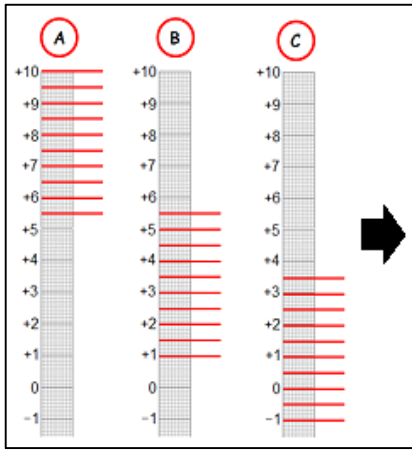
Fig. 1 – Proposed scale to assess a person's thermal feeling

3. The proposed method

In order to explain the procedure for data analysis let us imagine a hypothetical experiment where the three occupants of an office, whose temperature is 21 °C, are asked to assess their own thermal comfort at every each Celsius degree, while the room temperature increases up to 30 °C.

3.1 Experimental Matrix

After the data are gathered by means of the scale shown in Fig. 1, they are stored into a matrix called experimental matrix [11], as can be seen in Fig. 2.



°C	A	B	C	Averages
21.0	5.5	1.0	-1.0	1.8
22.0	6.0	1.5	-0.5	2.3
23.0	6.5	2.0	0.0	2.8
24.0	7.0	2.5	0.5	3.3
25.0	7.5	3.0	1.0	3.8
26.0	8.0	3.5	1.5	4.3
27.0	8.5	4.0	2.0	4.8
28.0	9.0	4.5	2.5	5.3
29.0	9.5	5.0	3.0	5.8
30.0	10.0	5.5	3.5	6.3

Fig. 2 – Experimental matrix for the hypothetical experiment proposed to validate the method.

The experimental matrix contains respondents' thermal feeling sensation as well as the average thermal feeling for each temperature level. Data in the experimental matrix depicted in Fig. 2 highlights the fact that each person feels the temperature in a different way and it varies from person to person as mentioned in section 1. The thermal feeling sensation is subject to several factors, so each person has his/her own thermal comfort scale.

Fig. 2 also shows that the average of the occupants' hot sensation increases as the room temperature increases. Because the room temperature is the only factor that changes during the experiment it seems that mean thermal comfort feeling is strongly affected by temperature, but, in order to be more objective, this conclusion needs to be confirmed by a statistical procedure.

3.2 Analysis of Variance (ANOVA)

It seems that the thermal comfort is affected by the environment temperature, but in order to be more objective in such analysis, it will be necessary to test for differences between the mean thermal feelings at all ten levels of the room temperature. In other words, the equality of the means should be tested [11], according to the hypothesis test (1).

$$\begin{cases} H_0 : \mu_1 = \mu_2 = \cdots = \mu_{10} \\ H_1 : \mu_i \neq \mu_j \end{cases} \quad (1)$$

Where $\mu_1 = \mu_2 = \cdots = \mu_{10}$ represents the mean thermal feeling for the ten temperature levels.

The appropriate procedure for testing the equality of several means is the analysis of variance (ANOVA). It will indicate if the null hypothesis should be, or not, rejected. Table 1 presents the summary of ANOVA for the experimental matrix showed in Fig. 2.

Table 1 – ANOVA for the experimental matrix in Fig. 2

Source of variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	$F_{critical}$	P-value
Between-Treatments	61.875	9	6.875	0.620301	2.392814	0.796774
Error (within-treatments)	221.6667	20	11.08333			
Total	283.5417	29				

Note that the between-treatment mean square (6.88) is smaller than the within-treatments mean, error mean square, (11.08). This usually indicates that there are not strong evidences to reject the null hypothesis (H_0). The F ratio F_0 (0.620) is less than $F_{critical}$ (2.392), which was determined for a significance level of 0.05, what also means that H_0 cannot be rejected. This result seems to contradict the expectations raised on the introductory paragraph of this section. This is a very important point: why ANOVA does not confirm the expectations? How does one explain this this apparent contradiction? What should be done to overcome this situation?

By taking a closer look at the experimental matrix in Fig.4, it seems that each person used a different scale to assess the thermal comfort feeling, so the variability of the thermal feeling for each temperature (each line of experimental matrix) is very large, becoming more significant than the variability between-treatments. Thus, it will be necessary to find out a way to convert all the inputs to a common scale so that the variability of the respondents' thermal feeling sensation for each temperature (each line of the experimental matrix) becomes smaller.

The answer can be the data standardization, which is a procedure usually used in data analysis when the input data comes from different scales. A standardized variable is a variable that has been rescaled to have a mean of zero and a standard deviation of one. The value of a standardized variable indicates its difference from the mean of the natural variable in number of standard deviations. The standardization procedure is the same used to obtain the z-scores. Table 2 presents the data from Table 1 standardized.

Table 2 – Standardized data from table in Fig. 2

°C	A	B	C	Averages
21.0	-1.5	-1.5	-1.5	-1.5
22.0	-1.2	-1.2	-1.2	-1.2
23.0	-0.8	-0.8	-0.8	-0.8
24.0	-0.5	-0.5	-0.5	-0.5
25.0	-0.2	-0.2	-0.2	-0.2
26.0	0.2	0.2	0.2	0.2
27.0	0.5	0.5	0.5	0.5
28.0	0.8	0.8	0.8	0.8
29.0	1.2	1.2	1.2	1.2
30.0	1.5	1.5	1.5	1.5

The average of the occupants' hot sensation presented in Table 2 follows the same pattern as the one shown in the raw data, i.e., it increases as the room temperature increases. Next, it will be necessary to examine whether ANOVA will confirm that the differences among the thermal comfort means are statistically significant. Table 3 summarizes the ANOVA for the data in Table 2.

Table 3 – ANOVA for the data in Table 2

Source of variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	$F_{critical}$	P-value
Between-Treatments	27	9	3	$\rightarrow \infty$	2.392814	$\rightarrow 0$
Error (within-treatments)	0	20	0			
Total	27	29				

It can be seen in Table 3 that the between-treatment mean square (3) is larger than the within-treatments, error mean square, (0). The F ratio F_0 tends to infinite, what means that H_0, can be rejected. This means that the room temperature significantly affects the mean thermal comfort feeling as expected, therefore it can be conclude that standardizing the data prior to conducting the ANOVA worked.

But before the conclusions from the ANOVA are adopted, the adequacy of the underlying model that represent the data should be checked. Therefore, the next step in data analysis will be the model adequacy checking, and the primary diagnostic tool is residual analysis [11], but this hypothetical experiment was designed to evaluate the necessity of data standardization and some properties of the scale, and then it was conceived without any kind of experimental error. Thus, there is no variability within-treatments as can be seen in Table 3. If the mean square error is zero, obviously the data fits perfectly to the model used for the analysis, whatever it is.

The ANOVA proved that there are differences between treatment means, but exactly which means differ is not specified. Sometimes, further comparisons and analysis among groups of treatment means may be useful. The procedures for making these comparisons are usually called multiple comparisons methods, among such procedures is the Tukey's test [11].

3.3 The Tukey's test

All of the multiple comparisons methods compare all pairs of treatment means according to the hypothesis test (2) [11].

$$\begin{cases} H_0 : \mu_i = \mu_j \\ H_1 : \mu_i \neq \mu_j \end{cases} \quad \text{for all} \, i \neq j \tag{2}$$

The Tukey's test is one of these procedures. It makes use of the distribution of the studentized range statistic to evaluate (2), more details can see in [11]. The Tukey's test declares two means statistically different if the absolute value of their sample differences exceeds:

$$T_\alpha = q_\alpha \sqrt{\frac{MSe}{n}} \tag{3}$$

Where,

q_α is a tabled value

MSe is the error mean square

n is the sample size

In the case of this hypothetical experiment, the error mean square is zero, therefore all the means are statistically different.

The data analysis can be made according to the flowchart shown in the Fig. 3.

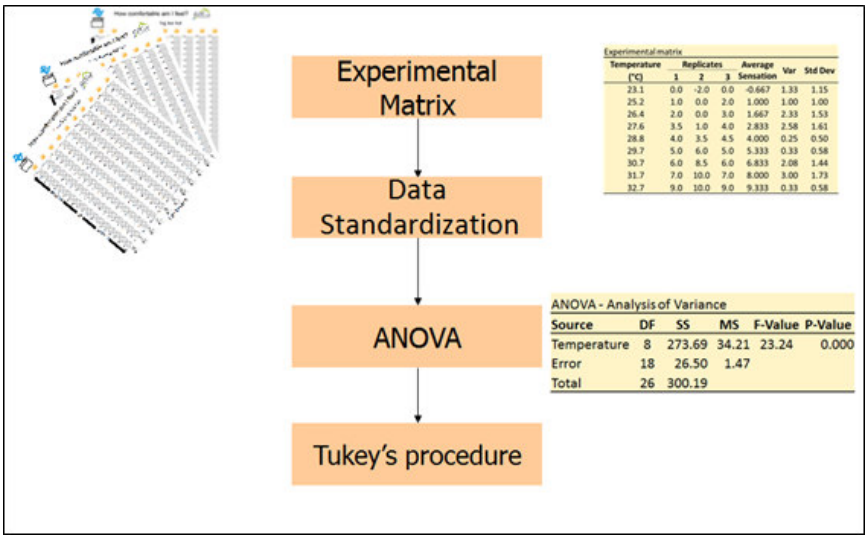


Fig. 3 – Data analysis procedure flowchart

This procedure will be applied to a real experiment conducted at G2Elab in Grenoble, described in [10], where the authors were interested in investigating whether the use of fans in a small office of the building can keep the thermal comfort level even when the room temperature increases.

4. A Case Study – The effect of fans on thermal comfort feeling

Bianchi *et al* [10], describes an experiment used to assess how the comfort feeling of a small group of people working in a small office is affected by the use of a fan. The target of such a research were to evaluate the potential of energy saving, making a combined use of HVAC systems and fans.

This experiment was performed in an office occupied by three PhD students, two males and one female, during two normal workdays in the cluster habitat, in G2Elab. During the experiment, the office temperature was slowly increased by 10°C, and from degree to degree, the occupants of the office were said to assess their thermal comfort by putting a mark on a scale of the chart shown in Fig. 4.

On the first day of the experiment, there were no fans operating in the office. During the second day, a fan operated full time at the maximum speed [10].

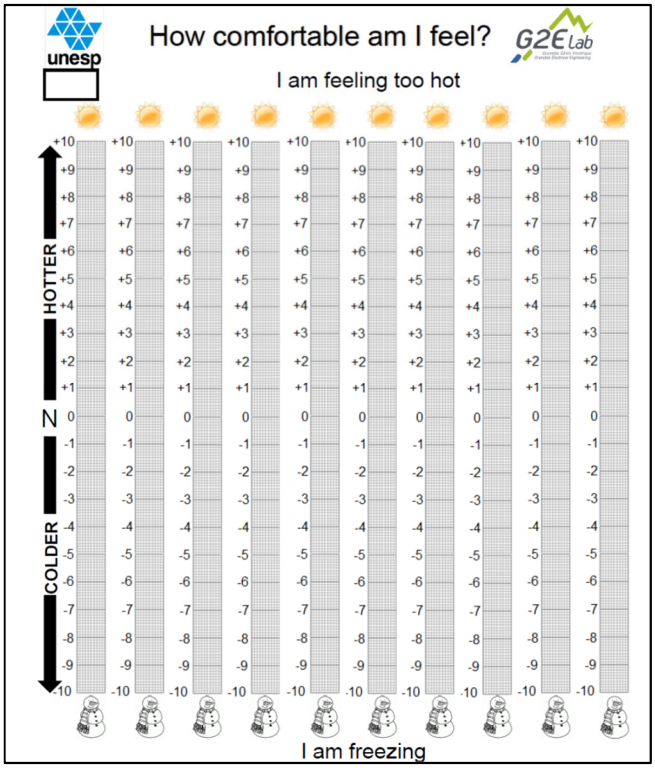


Fig. 4 – Measurement instrument designed to gather people's thermal sensation

The main objective of this experiment were to investigate whether the average thermal feeling has changed from one situation to another [10]. In order to improve the comprehension of this experiment, Fig. 5 illustrates its flowchart. For further information about this experiment consult [10].

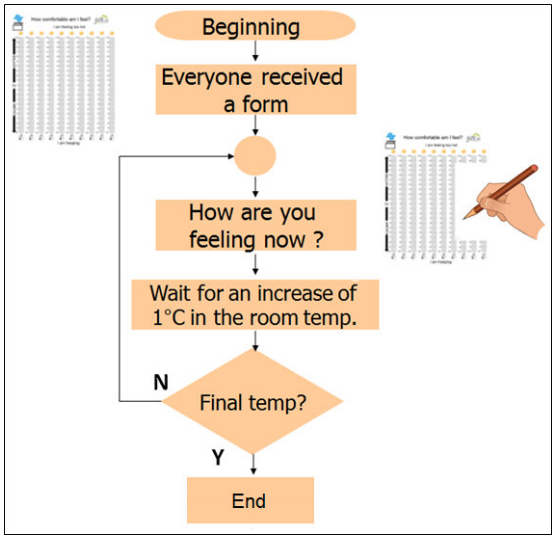


Fig. 5 – Experiment flowchart

4.1 Results

The first-day (fan-off) experimental matrix is shown in Table 4. As already occurred in the hypothetical experiment, each person felt the temperature in a different way.

Table 4 – The experimental matrix for the first-day (fan-off)

First-day (fan-off) - Raw Data					Standardized Data			
Temperature	Replicates			Averages	Replicates			Averages
	A	B	C		A	B	C	
23.1	0.0	-2.0	0.0	-0.7	-1.4	-1.3	-1.7	-1.47
25.2	1.0	0.0	2.0	1.0	-1.1	-0.9	-0.9	-0.97
26.4	2.0	0.0	3.0	1.7	-0.7	-0.9	-0.6	-0.73
27.6	3.5	1.0	4.0	2.8	-0.2	-0.7	-0.2	-0.36
28.8	4.0	3.5	4.5	4.0	-0.1	-0.1	0.0	-0.06
29.7	5.0	6.0	5.0	5.3	0.3	0.4	0.2	0.29
30.7	6.0	8.5	6.0	6.8	0.6	0.9	0.6	0.71
31.7	7.0	10.0	7.0	8.0	1.0	1.3	0.9	1.06
32.7	9.0	10.0	9.0	9.3	1.7	1.3	1.7	1.53

The average thermal feeling increases with temperature, as expected, but it is necessary to check if the differences between the means are statistically significant, so it is necessary to conduct the ANOVA. Its results are summarized in Table 5.

Table 5 – ANOVA for the experimental matrix for the fan-off

Source of variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	$F_{critical}$	P-value
Between-Treatments	23.424	8	2.928	91.433	2.510	0.0000
Error (within-treatments)	0.576	18	0.032			
Total	24.000	26				

Note that the between-treatment mean square (2.928) is greater than the within-treatments or error mean square (0.032). This indicates that it is unlikely that the treatment means are equal, therefore the hypothesis H_0 (equality of all means) can be rejected, what means that the temperature really affects the thermal comfort feeling, as expected. In order to see which means are different, Fig. 6 presents Tukey pairwise comparisons.

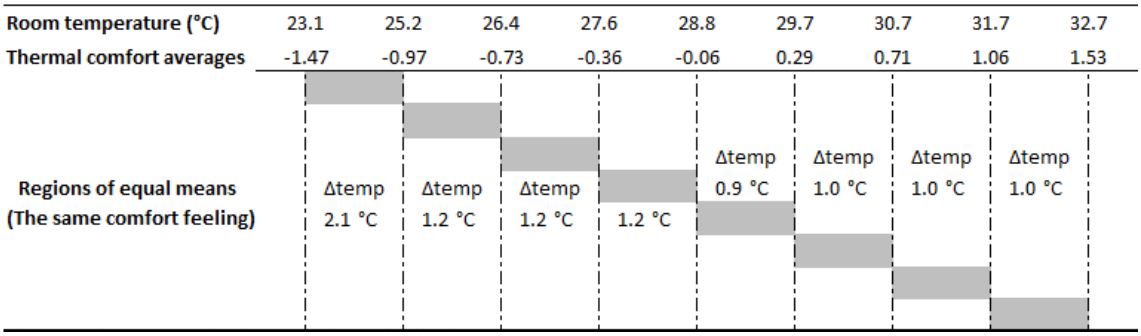


Fig. 6 - Tukey means pairwise comparisons for data in Table 4.

The gray area in Fig. 6 represents the region for which there is no significant difference between the means. For instance, there is no statistically significant difference between the means -1.47 and -0.97; -0.97 and -0.73 and so on. In other words, the gray areas are regions for which the thermal comfort are the same. It is possible to see that with the fan turned off, the hot feeling increases at every 1.2 °C.

The next step is to conduct the same procedure for the second-day experiment, which experimental matrix is shown in Table 6. Note that the respondent C reach the top of his/her scale almost three degrees before the others. The top of respondent A's scale is about the middle point of the other respondent's scale. In this case, as in the previous one, the average thermal feeling increases with the room temperature.

Table 6 – The experimental matrix for the second-day (fan-on)

Second-day (fan-on) - Raw Data					Standardized Data			
Temperature	Replicates			Averages	Replicates			Averages
	A	B	C		A	B	C	
23.4	0.0	2.0	-4.0	-0.7	-1.9	-2.0	-1.6	-1.85
25.4	1.5	4.5	0.0	2.0	-0.8	-0.8	-0.8	-0.80
26.5	1.5	5.9	2.0	3.1	-0.8	-0.1	-0.5	-0.45
27.6	2.5	6.0	1.0	3.2	0.0	-0.1	-0.7	-0.24
28.6	2.5	6.4	3.0	4.0	0.0	0.1	-0.3	-0.05
29.8	3.0	6.5	7.0	5.5	0.4	0.2	0.5	0.35
30.9	3.5	7.0	10.0	6.8	0.8	0.4	1.1	0.76
31.8	4.0	8.0	10.0	7.3	1.1	0.9	1.1	1.04
32.6	4.0	9.2	10.0	7.7	1.1	1.5	1.1	1.24

According to ANOVA, Table 7, the thermal comfort means are different, since the between-treatment mean square (2.870) is larger than error mean square (0.058). In other words, again the thermal feeling sensation is affected by room temperature. Now it is time to see which means are different.

Table 7 – ANOVA for the experimental matrix for the fan-on

Source of variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	F_0	$F_{critical}$	***P*-value**
Between-Treatments	22.960	8	2.870	49.678	2.510	0.0000
Error (within-treatments)	1.040	18	0.058			
Total	24.000	26				

The Fig. 7 illustrate the Tukey pairwise comparisons for this case, its interpretation is as the same as the one for Fig. 6, so when the fan is turned on, the thermal feeling also increases at every 1.2 °C.

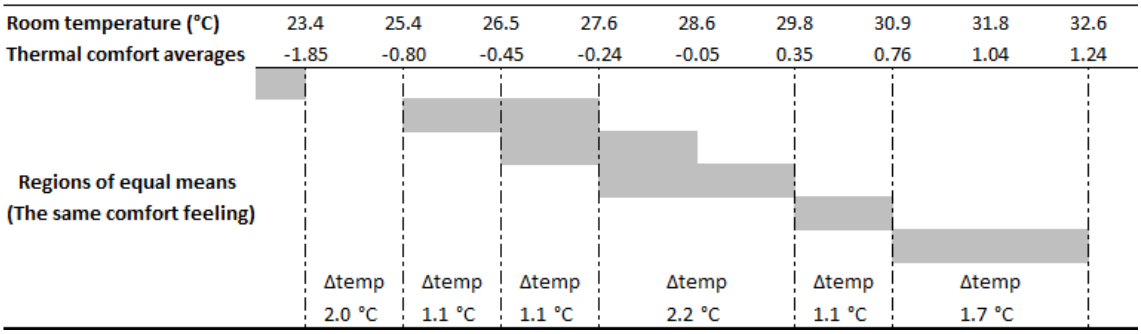


Fig. 7 - Tukey means pairwise comparisons for data in Table 6.

Then it is possible to conclude that, in this case, the fan did not contribute to decrease the hot feeling, maybe because it does not produce too much wind. Certainly, there are many hypotheses to test, but this does not belong to the scope of this paper.

5. Conclusions

This paper presented a procedure for thermal comfort assessment. This procedure includes a 10-points ratio scale; the standardization of the data gathered from the scale; the application of the analysis of variance to test for differences between the mean thermal feelings at all levels of the room temperature in which the thermal feeling was assessed; and the Tukey's test, that is a multiple comparisons method, to compare all pairs of treatment means.

A hypothetical experiment was designed in order to evaluate the proposed method. Afterwards the method was applied in a case study to investigate whether the use of fans in a small office of the building can keep the thermal comfort level even when the room temperature increases.

Finally, the proposed method proved to be useful and robust for thermal comfort assessment.

Acknowledgements

The authors acknowledge financial support from the People Program (Marie Curie Actions) of the

European Union's Seventh Framework Program FP7/2007-2013/ under project ELECON –Electricity Consumption Analysis to Promote Energy Efficiency Considering Demand Response and Non-technical Losses, REA grant agreement No 318912.

The authors acknowledge the financial support from IRT Nanoelec Program which received aid from the French State under the Future Investments program, with the reference ANR-10-AIRT-05 IRT.

Special thanks to Professor Stephane Ploix from G-SCOP/INPG for providing us with material and links and for important suggestions.

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