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THE APPLICABILITY OF LINEAR REGRESSION MODELS IN WORKING ENVIRONMENTS' THERMAL EVALUATION

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ABSTRACT

The simultaneous analysis of thermal variables with normal distribution with the aim of checking if there is any significative correlation among them or if there is the possibility of making predictions of the values of some of them based on others' values is considered a problem of great importance in statistics studies. The aim of this paper is to study the applicability of linear regression models in working environments' thermal comfort studies, thus contributing for the comprehension of the possible environmental cooling, heating or winding needs. It starts with a bibliographical research, followed by a field research, data collection and and software statistical-mathematical data treatment. It was then performed data analysis and the construction of the regression linear models using the t and F tests for determining the consistency of the models and their parameters, as well as the building of conclusions based on the information obtained and on the significance of the mathematical models built.

Keywords: regression models, thermal evaluation, working environments.

1. INTRODUCTION

Thermal comfort evaluation in working environments is a little explored area in Brazilian research. For that reason, specific technical literature on this topic presents some gaps. In spite of the existence of relevant contributions for the field, such as the ones developed by Araújo (1996), Gonçalves (2000), Xavier [17] e Hackenberg (2000), all cited in Gouvêa et al [6], there have not been regulations to guide Brazilian activities on the area produced yet. For that reason, the evaluations performed in this country have been based on regulations and procedures developed in other countries, which's thermal, environmental, and habit conditions differ from the Brazilian ones.

Thermal comfort studies are carried out in function of many variables which occur simultaneously. There have been noticed the need of some relationships establishment in order to predict one or more of these variables in function of the others. The use of mathematical-statistical models in this kind of evaluation will contribute for a better comprehension of the influence of the thermal variables, also contributing for a greater amount of knowledge in the area of projects and evaluations on working environments, taking into consideration the Brazilian climate conditions.

In this article, through a linear regression analysis, a working environment inner temperature was determined, based on the different human thermal sensations reported on different hours of the day. These data were compared to the operational temperature verified in the same hours as the ones reported by the human group.

2. THEORICAL FOUNDATIONS

In this section, the basic mathematical-statistic methods of parallel data will be introduced, with the aim at evaluating the relationship between two corresponding variables.

2.1. LINEAR REGRESSION MODELS

Given a set of parallel data, the Simple Linear Regression Model (SLRM), as presented by Charnet et al [3], describes the relationship between the two variables involved in this study, and can thus be summarised in Equation (1):

$$y_i = \beta_0 + \beta_1 \cdot x_i + \varepsilon_i \tag{1}$$

where β_0, β_1 and x_i have both constant values; $\mathrm{E}[\varepsilon_i] = 0$; $\mathrm{Var}[\varepsilon_i] = \sigma^2$; $\mathrm{Cov}[\varepsilon_i, \varepsilon_j] = 0$, for $i \neq j$ e $i, j = 1, \ldots, n$.

When the condition of the model of probability of the error is the normality, the corresponding simple sample linear regression model uses Eq.(1), which is subject to the following restrictions: β_0, β_1 and x_i have constant values; $\varepsilon_i \sim N(0; \sigma^2)$; $\mathrm{Cov}[\varepsilon_i, \varepsilon_j] = 0$ for $i \neq j$ e $i, j = 1, \ldots, n$. It is important to give emphasis to the fact that the parallel sample data are useful for the regression line estimation. It is not possible to determine the exact populational parameters values for β_0 and β_1 when only the sample data are known. However, it is possible to infer some results when minimum square estimators b_0 e b_1 are known. These estimators are commented by Triola [15] and are shown in Equations (2) and (3) bellow:

$$b_0 = \frac{\left(\sum y\right) \cdot \left(\sum x^2\right) - \left(\sum x\right) \cdot \left(\sum x \cdot y\right)}{n \cdot \left(\sum x^2\right) - \sum (x)^2} \tag{2}$$

$$b_1 = \frac{n \cdot \sum x \cdot y - \left(\sum x\right) \cdot \left(\sum y\right)}{n \cdot \left(\sum x^2\right) - \sum (x)^2} \tag{3}$$

These parameters represent, respectively, the intercept in *y* and the angular coefficient of the regression line below, as shown in Equation (4):

$$\hat{y}_i = b_0 + b_1 \cdot x_i \tag{4}$$

Additionally, Triola [15] defines, in this context, the marginal variation as the amount of variation by one variable when the other varies in exactly one unit. An analysis of linear regression and correlation of bivariate data must include an investigation about the extreme and influencing points, in this case. In a scatterplot diagram, an extreme point is the one which is much too far from the other ones. The parallel sample data, in turn, may contain one or more influence points, which are able to affect the regression line diagram strongly.

When the SLRM is considered, the valid relationship is the one shown in Equation (5) bellow:

$$\sum_{i=1}^{n}\left(y_i-\bar{y}\right)^2=\sum_{i=1}^{n}\left(y_i-\hat{y}_i\right)^2+\sum_{i=1}^{n}\left(\hat{y}_i-\bar{y}\right)^2 \tag{5}$$

This expression indicates that the total variation of y around of the $\bar{y}$ can be taken as the sum of the variation of y around the regression line, with the variation of the specific y expected values, for any value of y around of the $\bar{y}$. The Equation (5) provides the theoretical foundations for the concept of determination coefficient $r^2 \in [0;1]$, is the value of the y variation explained by the regression line, found by the use of Equation (6) (TRIOLA, [15]):

$$r^2=\frac{\sum_{i=1}^{n}\left(\hat{y}_i-\bar{y}\right)^2}{\sum_{i=1}^{n}\left(y_i-\bar{y}\right)^2} \tag{6}$$

According to Charnet et al [3] and Ragsdale [12], the multiple linear regression model describes the Y interes variable as a sum of deterministic and random parts. The deterministic part is the most general and for this reason the expected value Y can be expressed in two ways: as a function of many regression variables and (2) as a one-only regressing variable higher grade polynomials.

The suppositions on the error variable (ε) are the same previously defined for the simple linear regression. The theoretical foundation for the cases presented will be commented briefly. We might take, initially, the polynomial model with a regressing variable, which can be written as shown in Equation (7):

$$Y=\beta_0+\beta_1\cdot x+\ldots+\beta_k\cdot x^k+\varepsilon\text{, com }\varepsilon\sim N\left(0;\sigma^2\right) \tag{7}$$

Here, *x* is the fixed value of the regressing variable X . The parameters β_0, β_1, ..., β_k are the polynomials coefficient of *k* degree, which defines the expected values for Y, for a fixed value X . The Hyperplan model with three regressing variables is structured as Equation (8) bellow shows:

$$Y=\beta_0+\beta_1\cdot x_1+\beta_2\cdot x_2+\beta_3\cdot x_3+\varepsilon\text{, com }\varepsilon\sim N\left(0;\sigma^2\right) \tag{8}$$

In this model, x_j is the fixed value of the regressing variable X_j, for *j* = 1, 2 e 3; and the parameters β_1, β_2 e β_3 are the partial regression coefficients. Finally, the two regressing variables and interaction model is the one which is structured according to the following formation law, presented in Equation (9) bellow:

$$Y=\beta_0+\beta_1\cdot x_1+\beta_2\cdot x_2+\beta_3\cdot x_1\cdot x_3+\varepsilon\text{, com }\varepsilon\sim N\left(0;\sigma^2\right) \tag{9}$$

for x_i as a fixed value of the regressing variable X_i, *i* = 1 e 2.

Finally, the t and F statistical tests are applied, whose aim is verifying the consistency and the significance of the models and their parameters. Snedecor e Cochran (1989) apud Charnet et al [3] adds that, for the consideration in which the populations X and Y have bivariate normal distribution, the hypotheses: $H_0:\rho=0$ *versus* $H_1:\rho\neq 0$ can be tested, by using the statistics illustrated in Equation (10) bellow:

$$t = \frac{r \cdot \sqrt{n-2}}{\sqrt{1-r^2}} \quad (10)$$

H_0 has a t Student distribution, with *(n-2)* degrees of freedom, n is the size of the sample, r is the correlation coefficient and r^2 is the determination coefficient.

Magalhães and Lima [10] state that, in the value dispersion study of two populations $X \sim N(\mu_X, \sigma_X^2)$ and $Y \sim N(\mu_Y, \sigma_Y^2)$, based on their variances, the amount F is used (Equation 11) for testing as hypotheses: $H_0 : \sigma_X^2 = \sigma_Y^2$ *versus* $H_1 : \sigma_X^2 \neq \sigma_Y^2$. Thus, the amount F, as it is explained bellow, is based on the sample obtained from the population of interest, whose variances are being compared. So,

$$F = \frac{S_X^2}{S_Y^2} \quad (11)$$

S_X^2 and S_Y^2 are the sample variances of the populations X and Y, respectively. Under H_0, it is known that F follows the model of Fisher-Snedecor, which is characterized by the degrees of freedom associated to the amounts found in the numerator and in the denominator of Equation (11), in this case $n_1 - 1$ and $n_2 - 1$, respectively.

2.2 THERMAL COMFORT

Coutinho [4] defines thermal comfort as "a state of spirit which reflects the satisfaction of one person with the environment in which this person is inserted" [authors' translation]. Between the years of 1970 and 1986, some researches have proved that thermal comfort is strictly related to the thermal equilibrium of the human body, and that this equilibrium is influenced by environmental and personal factors (RUAS [13]).

Many of the researches performed in laboratories and in the field have been developed in order to verify the relationship between the thermal comfort and the development of a person (FANGER [5]). In spite of not having come to a definitive conclusion, these researches show a trend, in the results, that the uncomfortable feeling in cool or hot environment might reduce the performance of a person (XAVIER, [17]).

In the same way, Fanger [5] believes that the first condition for a human being to feel comfortable thermically is that this person must be in a thermal balance. According to ASHRAE - American Society of Heating and Air-Conditioning Engineers (1997), this balance can be represented by Equation (12), where all of the parcels have the unit $[\mathrm{W/m^2}]$.

$$M - W = Q_{SK} + Q_{RES} + S = (C + R + E_{SK}) + (C_{RES} + E_{RES}) + (S_{SK} + S_c) \quad (12)$$

where

M = rate of metabolic heat production, W/m²

W = rate of mechanical work accomplished, W/m²

Q_{SK} = total rate of heat loss from shin, W/m²;

Q_{RES} = total rate of heat loss through respiration, W/m²;

C+R = sensible heat loss from skin, W/m²;

E_{SK} = rate of total evaporative heat loss from skin, W/m²;

C_{RES} = rate of convective heat loss from respiration, W/m²;

E_{RES} = rate of evaporative heat loss from respiration, W/m²;

S_{SK} = rate to total evaporative heat loss from skin, W/m²;

S_c = rate to heat storage in core compartment, W/m².

As it was stated, all of the thermal balance parcels are measured in watts per square meter of body surface. This unit is based on Dubois area (A_{DU}), as represented by Equation (13) ASHRAE [2]:

$$A_{DU} = 0{,}202 \cdot m^{0{,}425} \cdot l^{0{,}725} \qquad (13)$$

where A_D = Dubois surface area, m^2; m = mass, kg; and l = height, m.

The inner temperature of the human body is controlled by the thermal regulation system, which makes it easier or more difficult the heat rejection, by expanding or contraction of the peripheral blood veins, by sweating or by the thrilling. Thus, we can assume that, out of a determined comfort range, the thermal balance is obtained by the body effort. In these occasions, people feel hotter or colder. However, this sensation varies from one person to another, due to individual subjectivity, as Fanger [5] comments.

This fact has taken Fanger [5] to define an index called PMV (Predicted Mean Vote), which is determined in function of the thermal balance and of the opinion of a population statistically representative, as it is mathematically explained in Equation (14):

$$PMV = \left(0{,}303e^{-0{,}036M} + 0{,}028\right) \cdot \left\{(M - W) - 3{,}05x10^{-3} \cdot \left[5733 - 6{,}99 \cdot (M - W) - p_v\right] - \right. \qquad (14)$$
$$- 0{,}42 \cdot \left[(M - W) - 58{,}15\right] - \left[1{,}7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a)\right] - \left[0{,}0014 \cdot M \cdot (34 - t_a)\right] -$$
$$\left. - \left\{3{,}96 \cdot 10^{-8} \cdot f_{cl} \cdot \left[\left(t_{cl} + 273\right)^4 - \left(\bar{t}_r + 273\right)^4\right]\right\} - \left[f_{cl} \cdot h_c \cdot \left(t_{cl} - t_a\right)\right]\right\}$$

M and W were previously defined, remaining to be explained:

p_v = Partial water steam pressure, measured in [kPa];

t_a = Air temperature, in [°C];

t_{cl} = Clothes' temperature, in [°C];

$\bar{t}_r$ = Medium radiant temperature, in [°C];

h_c = Convection coefficient, in [W/m²·°C];

f_{cl} = Ratio of man's surface area while clothed, to man's surface area while nude.

This index is represented by a range of values in which each value corresponds to a certain thermal sensation (S). This sensation is specified by the following labels of values: -3 = too cold; -2 = cold; -1 = slightly cold; 0 = neutral; +1 = slightly hot; +2 = hot; +3 = too hot.

Naturally, it was verified that, at each thermal sensation level, there was a specific number of people which were not satisfied with it. This situation was represented by another index, named PPD (Predicted Percentage of Dissatisfied), as Equation (15) shows:

$$PPD = 100 - 95 \cdot e^{-\left(0{,}03353 \cdot PMV^2 + 0{,}2179 \cdot PMV^2\right)} \qquad (15)$$

The two indexes presented are adopted by the Regulation ISO 7730 [8], which is used in the evaluation of thermically moderated temperature environments. Still, it is important to mention the definition for operative temperature $\left(t_{op}\right)$: according to ASHRAE [1], it is the uniform temperature of an imaginary environment, in which a person changes the same amount of heat (by convection or radiation) as it would be in a real environment, calculated by Equation (16) below. All the variables in this equation were previously defined, except for h_r (coefficient of radiation, measure by the same unit of h_c). So,

$$t_{op} = \frac{h_r \cdot t_{rm} + h_c \cdot t_{bs}}{h_c + h_r} \tag{16}$$

ASHRAE [2] relates four important factors that may contribute for the localized uncomfort sensation, listed as follows:

- Assimetry of thermal radiation: caused by surfaces of windows, outer surfaces non-insulated, oven heat, machines and other elements;
- Undesirable air blowing;
- Differences in the temperature of the air in the vertical direction – Olesen, McNair and Erikson apud ASHRAE [2], have related that, if the temperature at the head level is smaller than the one at the ankle level, probably there will not be any thermal uncomfort sensation; in these conditions, people have shown more tolerant;
- Contact with hot or cold floor;
- Physiological, psychological physical and behavioral factors, which are inherent, respectively, to the human body, to the stimulus-answer relationship, to the processes of human heat transfer and the interaction of the man and the environment.

3. METHODOLOGY

The methodology applied in this study has had two fundamental bases: a) Theoretical: Tabachnick and Fidel [15], Levine et al [11], Charnet et al [3] and Ragsdale [12]; and b) Experimental: software Statistica version 5.0 – descriptive statistical and linear regression analyses; software Excel version 7.0 – Bera-Jarque normality test. This methodology consisted of the development of the following tasks:

a) Evaluation of the climate conditions in the working environment in a bank sector of the city of Recife (PE), Brazil, by the use of the equipments of Labour Analysis Laboratory of the Production Engineering Department at Federal University of Paraíba, which are under the demands of the ISO/DIS 7726/1996 [7]. Some questionnaires were distributed with all the participants of the research, for that they could register their opinions about their thermal sensation, kind of clothes they used and personal data, according to the demands of ISO 10551 [9] (Subjective Judgment Scales) Regulation.

b) Verifying, through BOX-COX, the normality of the collected samples in the environment being studied. This is a Bera-Jarque normality test, which is a consequence of the study performed by Shenton and Bowman [14]. This study consists of the expressions for curtosis and assimetry, according to Equation (17):

$$N\left[\frac{\sqrt{b_1^2}}{6} + \frac{\left(b_2 - 3\right)^2}{24}\right] \approx \chi^2 \tag{17}$$

where:

$\sqrt{b_1^2}$ = Asymmetry; b_2 = Curtosis and χ^2 = Chi-square.

When b_1 and b_2 have big values, the value for the expression above is higher than the table Chi-square (χ^2). That is to say, if the results of the test applied to the collected variables are beyond 5,91, which represents 2 degrees of freedom and a frequency of 0,95 in a Chi-square table, the sample related to the tested variable will not follow a normal curve.

c) Building of a model of linear regression. According to Tabachnick and Fidel [15], Levine et al [11], Charnet et al [3] and Ragsdale [12], the general model of a linear equation can be expressed as a dependent variable (VD) in function of a set of independent variables (VI).That is to say, the dependent variable expected value can be expressed as a function of many regressing variables (VI). Thus, the model in Equation (18) was used, based on the Equation (1) already mentioned, now presenting the following format and incorporating each meaning to the constitutive elements shown below:

$$y_P = \beta_0 + \beta_1 \cdot x_1 + \varepsilon \qquad (18)$$

where:

y_P = Dependent variable (S – thermal sensation) predicted by the variable of thermal comfort;

β_0 = Regression Constant variable or intercept;

β_1 = Partial coefficient or regression parameter for the variable x_1;

x_1 = Operative temperature in $[^{o}\mathrm{C}]$;

ε = Error or residual, due to the regression model (statistical and non-deterministic).

d) Verifying, through *t* and *F* tests, the consistency of the equation and of its parameters;

e) Determining the thermal comfort inner temperature for the studied environment, according to the perception of the people taking part in the experiment.

4. RESULTS E DISCUSSIONS

Some bank activities are performed in the working environment studied. This means that these are slow activities by people using light clothes. The data used in the experiment were collected for three days. These data are related to the climate variables and to personal variable, such as S (thermal sensation), age, height, and weight. It important to call the attention to the fact that the unities attributed to the variables I_{cl} e V_{ar} are, respectively, $[\mathrm{clo} = 0{,}155\,\mathrm{m}^2 \cdot {}^{o}\mathrm{C/W}]$ and $[\mathrm{m/s}]$. The comfort inner temperature, determined from the collected data was obtained taking into consideration the votes of the sensations reported by the people at the various hours of the day, in comparison to the operative temperature (t_{op}) verified at those hours of the day.

On the other hand, it is important to highlight that, in this experiment, there was no need to use the multiple regression. This happens because in the selected environment for the thermal evaluation various heat changes were registered (such as printers, computers, and the human body). Also, as (t_{op}) is a weighed value between the variables t_a and $\bar{t}_r$, the proposed model has involved one dependent variable (S) and only one independent variable (t_{op}). It is also important to give emphasis to the fact that it could be presented, for instance, the dependent variable (productivity) in function of the variables explained above and of the psychological variables, in order to show, in future studies, the consequences of these variables on the productivity variability of the people taking part in the experiment. The results related to the statement would contribute to a higher quality in the working environment, as a consequence of the productivity.

It was verified, through the BOX-COX measures, the normality of the variables above, according to the Equation (17), as it can be seen on Table (1) below.

Table 1. Experimental values of the coefficients (Distortion, Curtosis and Bera-Jarque) related to each of the variables involved in the sample space.

Coefficients	I_{cl}	t_a	t_{bu}	$\bar{t}_r$	V_{ar}	UR	t_{op}	S
Coef. Distortion	-0,79083	1,015	2,408	0,7473	2,796	3,0206	0,9448	0,02
Coef. Curtosis	1,366008	-0,4	5,357	0,062	7,964	8,3185	-0,113	-0,72
Bera-Jarque	0,209554	0,176	1,597	0,1247	3,109	3,3867	0,158	0,02

The *t* and *F* testes have shown that the consistency of the model, as well as of its parameters were highly significative (*p*-level = 0,00000, for $\alpha = 0{,}05$).

Through linear regression analysis and its adjustment line, it was obtained a regression equation for the calculus of the sensation in function of the operative temperature (t_{op}).

For the situation of full comfort sensation $S = 0$, the temperature determined by the equation is considered as the body inner temperature of comfort. The figure1 shows this analysis. It also shows the model and the ideal temperature under the people's thermal sensation.

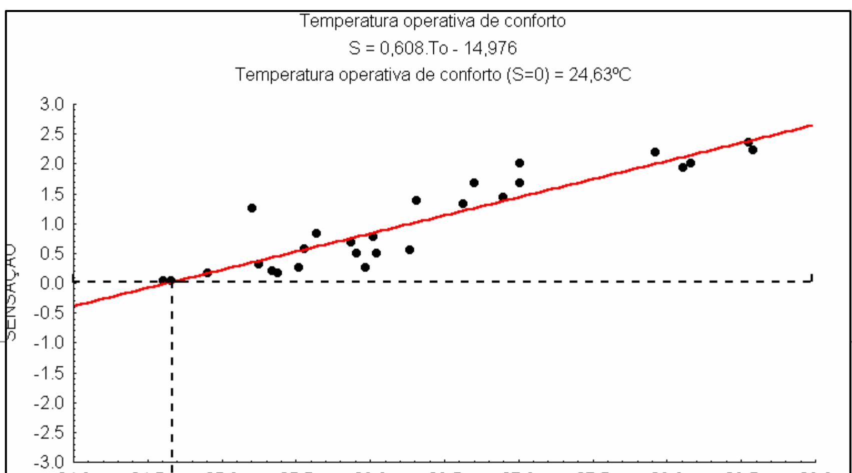

Figure 1. Regression line drawn between operative temperatures and the corresponding sensations reported by the people that took part in the experiment.

5. FINAL CONSIDERATIONS

It can be observed, in figure 1, that the value of r^2 is close to 1, since the points of the scatterplot diagram can be found around the regression line. This statement show that the regression models can provide a value as answer, which is based on the values of at least one indepedent or explaining variable. In this study, it was determined Equation (19) from the experimental data:

$$S = -14{,}976 + 0{,}608 \cdot t_{op} \quad (19)$$

and, for $S = 0$, what means thermal comfort sensation, it can be stated that the ideal temperature for the people working in the studied environment is 24,63ºC. That is to say, from this regression model, and taking into consideration the meaningful number of data collected, some thermal satisfaction and effective use of power can be obtained in the next computer working environment designs or of any other kind of environment, which is similar to the one studied here.

Given the statements present, the conclusion that can be drawn is that the application of linear regression models on the variables involved in the computer working environment thermal evaluation may contribute for the perception especially of the plant designer, of possible climate, heating or winding needs, with a goal of obtaining the comfort conditions determined from the results generated by the models and supported by the national an international regulations.

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APLICABILIDADE DE MODELOS DE REGRESSÃO LINEAR EM AVALIAÇÕES TÉRMICAS DE AMBIENTES DE TRABALHO

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RESUMO.

Um problema de grande importância no estudo de variáveis térmicas que possuem distribuição normal é a análise simultânea entre elas, com a finalidade de averiguar se existe alguma correlação significativa entre as mesmas ou de investigar a possibilidade de se fazer previsões a respeito dos valores de uma das variáveis correlacionadas, com base no conhecimento dos valores das outras. Este trabalho propôs-se a estudar os modelos de regressão linear a fim de aplicá-los em pesquisas realizadas sobre o conforto térmico de ambientes, contribuindo assim para a compreensão das possíveis necessidades de refrigeração, aquecimento ou ventilação para um ambiente de trabalho.Inicialmente, partiu-se da pesquisa bibliográfica, seguida da pesquisa de campo, coleta de dados e tratamento matemático-estatístico destes em software específico.Por fim, procedeu-se à análise dos dados coletados e construção dos modelos de regressão, utilizando-se os testes t e F para verificar a consistência dos modelos e de seus parâmetros, bem como à estruturação de conclusões baseadas nas informações colhidas e na significância dos modelos matemáticos equacionados.Palavras-chave: modelos de regressão, avaliação térmica, ambiente de trabalho.

Palavras-chave: Modelos de regressão. Avaliação térmica. Ambiente de trabalho.