# A multiple linear regression approach to correlate the Indoor Environmental Factors to the global comfort in a Zero-Energy building

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**Abstract.** The quality of the indoor environment, in terms of thermal, lighting, air and acoustic quality, grouped in the Indoor Environmental Quality (IEQ) concept, plays a key role in occupants' wellbeing and satisfaction. Only in recent years IEQ has been investigated as a whole. Today, IEQ occupies the same place of energy efficiency in the design of buildings, especially those with high performance level as the Zero-Energy Buildings (ZEB). The research deals with an experimental campaign during the cooling season carried out in a ZEB laboratory that involved 100 participants aimed at evaluating the IEQ and the indoor environments (e.g. thermal and air quality). The test consists in a survey, during which each participant is required to answer a questionnaire about how he feels the indoor environment. The experimental campaign was completed with a monitoring activity aimed at detecting the main environmental variables that can affect the participants' answers. Collected data were treated with regression techniques to highlight possible relationships between them. The results show how in a building with high levels of energy performances the air quality plays a key role on occupants' evaluation.

## 1 Introduction

The Directive 2010/31/UE and the recent Directive 2018/844/EU identify building sector as key actor in the European energy policies, promoting both the construction of high energy efficient buildings and a long-term cost-effective renovation strategies for the refurbishment of the existing building stock toward near zero energy target, with a strong attention to health and well-being of building's users [1, 2]. Inside buildings, Indoor Environmental Quality (IEQ) and users' well-being are strictly linked [3]. IEQ is widely investigated and many findings about how the indoor quality affects human life were defined [4]. However, in the field of low energy buildings, that represent the current target for new and retrofitted buildings [5], few studies focused on IEQ and well-being effects [6], emphasizing the energy aspect [7, 8]. In these buildings where the environmental variables

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are often automatically controlled by dedicated systems and the users' role in this task is low, attention must be paid on IEQ, avoiding possible discomfort [9, 10].

All indoor environment factors of IEQ (i.e. Thermal Comfort, Visual Comfort, Acoustic Quality and Indoor Air Quality) play a fundamental role in guaranteeing an acceptable overall condition in different types of indoor spaces [11, 12, 13]. Often these aspects are treated as disaggregated.

The article presents the results of a survey carried out involving 100 participants in a Zero Energy Building Laboratory (ZEB Lab) about their overall satisfaction respect to the environment.

## 2 ZEB laboratory and monitoring system

The research was carried out in a ZEB laboratory located in San Giuliano Milanese, near Milan, and involved 100 participants who is asked to answer a questionnaire about how they perceive specific aspects of IEQ. More details about the buildings are provided in [14]. The experiment was carried out in room 1 (see Figure 1).

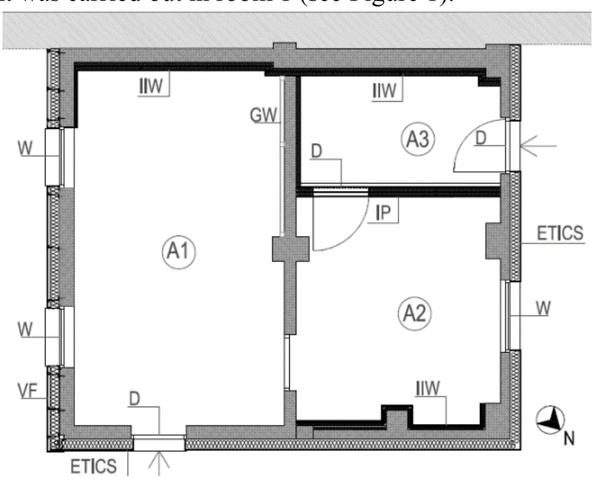


**Fig. 1.** Plan of the laboratory.

The HVAC systems consists in a direct expansion air conditionned system. he air change per hour was ensured by two ventilation systems each set at 30 $m^3/h$. The illuminance level value between 300 and 500 lux, according to EN 12464 on the desk surfaces was ensured by a combination of natural and artificial light. Finally, the adopted experimental setup considers also different sensors placed closest to the participants: 1 thermo-hygrometric sensor, 1 globe-thermometer, 1 hot wire anemometer, positioned in accordance with the requirements provided by EN ISO 7726, 1 $CO_2$ concentration sensor, positioned in accordance with EN ISO 16000-26, 1 luxmeter, positioned on the desk and 1 microphone positioned at the listening height, as per IEC 60268-16. The experimental campaign consists of an experience lasting a total of 30 minutes, including the initial acclimatization, response to questionnaire and data collection. During the acclimatization period, each participant was asked to fill out a first questionnaire about his physical parameters (age, weight and height) and clothing. The participants were asked to remain seated and watching video on a personal computer. After the experience, a second questionnaire were submitted about the subjective evaluation of the environment.

# 3 Method

## 3.1 IEQ evaluation

A questionnaire has been defined according to Standard EN ISO 28802 with the aim of investigating Thermal Comfort - TC, Indoor Air Quality - IAQ and IEQ. For each issue, evaluative scales are provided, as suggested by EN ISO 10551. The 4-degree one-pole scales are built to assess how person feel the environment from 0 (Comfortable) to 3 (Very uncomfortable). 5 simple questions about each issue were asked to participants, structured for example as follows:

*How does it feel to be the thermal environment?*
*0 – Comfortable*
*1 – Slightly Uncomfortable*
*2 – Uncomfortable*
*3 – Very Uncomfortable*

The questionnaire was submitted at the end of experience that involves a heterogeneous sample of 100 participants.

Then, the responses were analysed using a multiple linear regression to understand how the environmental factors contribute to identifying IEQ and whether there are dependencies among them.

## 3.2 Multiple linear regression

The relation among IEQ, TC and IAQ can be described by regression functions multiple linear or non-linear. In general, the approximation can be represented by the following equation:

$$y = \beta_0 + \beta_A * x_A + \beta_B * x_B + \beta_{AB} * x_A * x_B + \varepsilon \quad (1)$$

Where y is the occupants' evaluation of the IEQ, xi are TC and IAQ, $\beta_i$ are the main coefficients, $\beta_{i,j}$ are the interaction coefficients and ε is a random error of each observation. Then, the phenomenon can be studied by a multiple linear regression, as the following equation.

$$y = \beta_0 + \beta_i * x_i + \varepsilon_i \quad (2)$$

Additionally, residuals analysis and statistical tests F and *t* can be used to assess the suitability of the regression model and to determine the significance of main interaction effects involved, respectively.

A multicollinearity analysis is carried out to analysis the existence of strong correlation among TC and IAQ. Indeed, strong correlation does not allow their effect on the variable IEQ to be identified.

The measurement of the multicollinearity is based on the Variance Inflationary Factor (VIF), calculated for each environmental factor with the following equation.

$$VIF_i = 1/(1-R^2_i) \tag{3}$$

Where $R_i^2$ is the coefficient of determination that characterizes the dependent variable IEQ and the independent variables TC and IAQ. When VIF is close to 1, TC and IAQ are not correlated. If VIF > 5 it means that the variables are correlated (22).

Once assessed the adequacy of the regression model it is possible to verify the presence of a relationship among IEQ and TC and IAQ. The verification of this hypothesis is solved with the Test F (ANOVA method).

$$F = MSR/MSE \tag{4}$$

Where MSR is the mean square due to regression (explained variance) and MSE is the mean squared error (known also as unexplained variance). The subsistence hypothesis of a relationship is accepted if F>Fcr, where Fcr is the critical value on the right queue of the distribution F with a significance level p of 0.05.

Test *t* is introduced to verify the hypothesis of the slope in the multiple regression model, like TC and IAQ have a significant effect on IEQ. To verify the hypothesis the following formula is used.

$$t_i = \beta_i / SE_{\beta i} \tag{5}$$

Where $\beta_i$ represents the estimate of the expected variation of IEQ associated with a unitary variation of TC and IAQ, respectively, keeping fixed the rest of the model. $SE_{\beta,i}$ is the Standard Error of the regression coefficient $\beta_i$.

## 4 Results and discussion

The ZEB lab follows the design criteria for the optimization of IEQ, according to EN 16798-1 and EN 12464. Throughout the whole period, the temperature fluctuated between 25.1°C and 26.4°C. Only during the last two days of the experiment, the temperature reaches 29°C. The relative humidity fluctuated between 50% and 60%. In only two days it exceeded 60% (Figure 2). Illuminance level is everyday over 600 lx, only one day is just above 400 lx. The $CO_2$ concentration is always between 600 and 900 ppm.

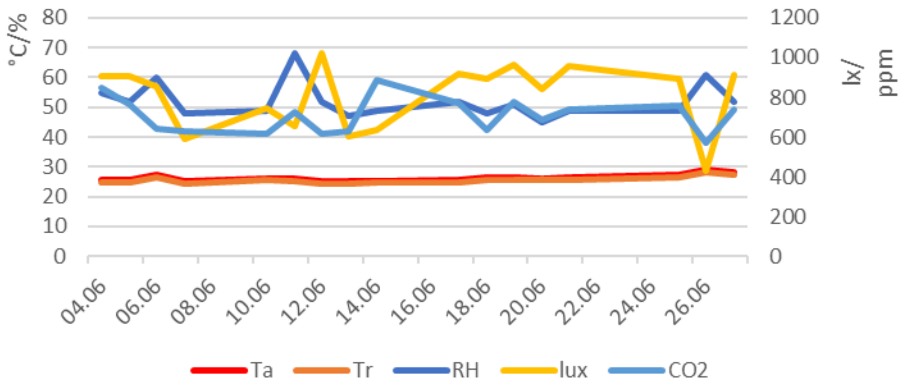


**Fig. 2.** Daily average of indoor environmental quantities.

### 4.1 Questionnaire results

A total number of 100 questionnaires were collected. The results of the questionnaire (Figure 3) indicate about the TC: 25% Comfortable; 57% Slightly uncomfortable; 17% Uncomfortable; 1% Very uncomfortable. Only on June 17th one participant gave a rating equal to 3. On the other hand, the participants evaluation in terms of air quality are: 17% Comfortable; 38% Slightly uncomfortable; 28% Uncomfortable; 17% Very uncomfortable.

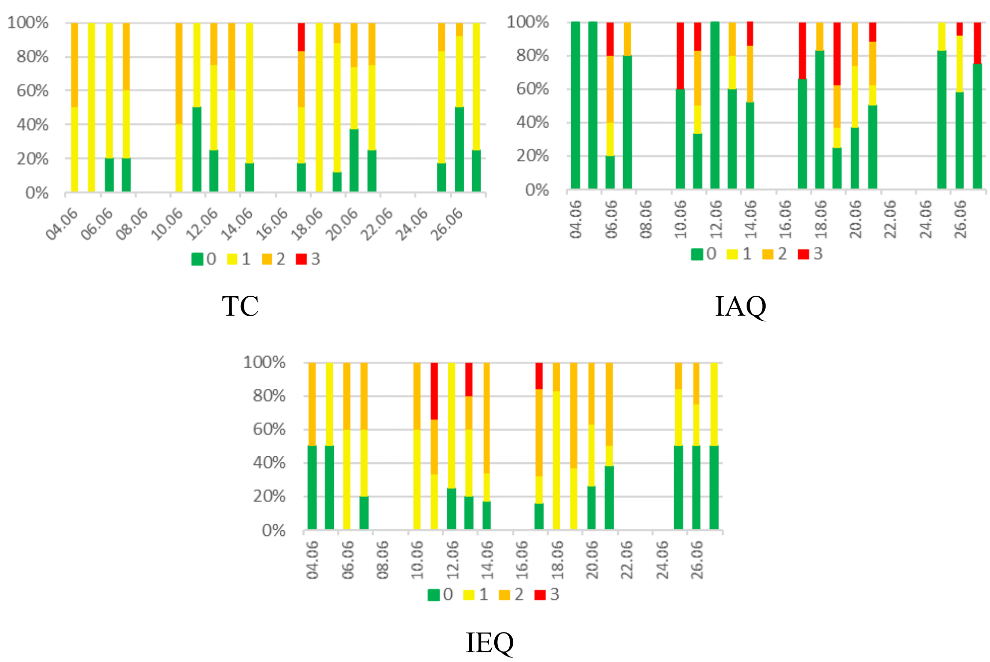


**Fig. 3.** Daily distribution of TC, IAQ and IEQ.

IEQ evaluation is mainly considered comfortable. In particular: 60% Comfortable; 35% Slightly uncomfortable; 5% Uncomfortable; 0% Very uncomfortable. However, looking at Figure 4, in answer to the question: "What is the cause of greater discomfort?", 66 people do not detect any discomfort. 11 people think IAQ can be improved; 7 people would like to improve the air temperature; 8 people consider AQ as the major cause of discomfort, while VC is to be improved for 2 people and 6 people consider RH as the main cause of discomfort.

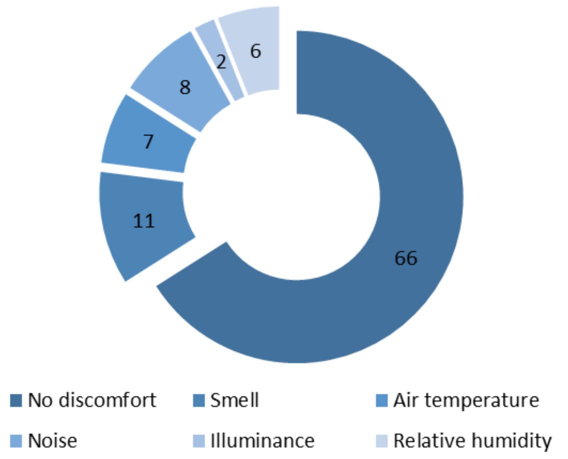


**Fig. 4.** Main causes of discomfort.

## 4.2 Discussion

The correlation coefficients in Table 1 do not show strong links between variables. However, what can be highlighted is the highest R-value between IEQ and IAQ. In addition, some correlations have negative signs. These phenomena, which can be seen from a statistical analysis, are not reflected in the described reality.

**Table 1.** Matrix of correlation coefficient R.

| | TC | IAQ | IEQ |
|---|---|---|---|
| **TC** | 1 | | |
| **IAQ** | -0.20 | 1 | |
| **IEQ** | 0.11 | 0.72 | 1 |

There is not multicollinearity between variables. All VIF values are less than 5. Therefore, it is not necessary to exclude any variables. According to ANOVA method and considering a level of significance of $p = 0.05$ with 16 degrees of freedom, the following analysis is obtained. Firstly, using the ANOVA method, there is a relationship between IEQ and the independent variables when F is greater the critical F (Table 2).

**Table 2.** ANOVA - IEQ.

| | SS | MS | F | Significance F | Critical F |
|---|---|---|---|---|---|
| **Regression** | 0.77 | 0.38 | 9.93 | 0.002 | 3.63 |
| **Residuals** | 0.54 | 0.04 | | | |

Test *t* was performed trying to identify the correlation indices between TC, IAQ and IEQ (Table 3).

**Table 3.** t Test.

| | Coefficient | SE | t Stat | Significance value |
|---|---|---|---|---|
| **Intercept** | 0.011 | 0.13 | 0.09 | 0.931 |
| **TC** | 0.27 | 0.17 | 1.53 | 0.149 |
| **IAQ** | 0.70 | 0.16 | 4.41 | 0.001 |

*t* table value (+ 2.12) is compared with each *t* Stat. Therefore, the only explanatory variable that has a significant effect on IEQ is IAQ.

The complete formulation of the regression equation is then:

$$IEQ = 0.011 + 0.27\ TC + 0.70\ IAQ \quad (6)$$

The unknown variable is the occupants' evaluation of the IEQ. The ANOVA method suggests a greater weight of IAQ.

## 5 Conclusions

The article shows how IEQ evaluation is affected mainly by IAQ conditions within a ZEB, even if the equation cannot be generalised to all air-conditioned office buildings. In fact, a zero-energy building is designed by considering infiltrations equal to 0 and a HVAC system whose task is to change the air and recover the outgoing heat. In Zero-Energy buildings where the environmental variables are often automatically controlled by dedicated systems and the users' role in this task is low, attention must be paid on IEQ. In this context the role of IAQ becomes very important to control RH, CO2 and VOCs.

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