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Objective and subjective evaluation of thermal comfort in the Loccioni Leaf Lab

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Abstract

Thermostatically controlled loads in commercial buildings are usually ruled by set points indicated by well-established international standards like EN 15251. These thresholds set the acceptable comfort ranges based on several parameters such as activity level, climatic conditions and building orientation. However, there are so many aspects which can affect the occupant perception of comfort ranging from physical and mental aspects to cultural aspects while only few of them are clearly measurable.
This paper presents a methodology for the simultaneous subjective and objective evaluation of thermal comfort in commercial buildings. The methodology is based on the intermediate protocol level for the evaluation of thermal comfort as suggested by ASHRAE's *Performance Measurement Protocols for Commercial Buildings.* It is applied in the office spaces of the Loccioni Leaf Lab, located in the province of Ancona, Italy, during the summer period. The study is utilized for the identification of serious thermal comfort issues but also for the determination of the preferred comfort conditions in the Leaf Lab office spaces.

Keywords: thermal comfort, industrial buildings, internal comfort, subjective parameters, user preferences.

1. Introduction

People expect to be comfortable in the buildings they occupy. In order for their needs to be met, the building and its systems need to be designed to serve this purpose.

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A large number of factors such as energy efficiency, climate variations, occupants' health and comfort requirements, and many more, need to be taken into consideration in this process [1]. There are so many aspects which can affect the thermal perception and comfort of people, ranging from physical and mental aspects to cultural aspects [2-4], and few of them can be easily measured. The relationship between two of the first concepts of thermal comfort, the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD), also indicates that it is impossible to satisfy all persons in a large group in the same thermal environment [5,6].

The PMV, initially conceived by Fanger [7], is a 7-point thermal sensation scale that that predicts the mean value of the votes of a large group of people that are exposed to the same environment according to the heat balance of the human body [5,8]. Predicted Percentage of Dissatisfied is an index that quantifies in a percentage the thermally dissatisfied people determined from the PMV [5]. The six primary factors that are considered in those indices are: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity. Well established international standards like [5,6,9] consider the PMV and PPD indices for the evaluation of thermal comfort conditions [10]. Thermal comfort can be evaluated with both objective and subjective methods. Objective methods involve physical measurements of thermal comfort parameters. In subjective methods the building users themselves are asked to evaluate their thermal environment in terms of thermal sensation, acceptability, preference for change and more through occupant surveys [11].

This paper presents the findings of the study of objective and subjective thermal comfort in an office building in Italy. The approach followed for this study is based on the intermediate protocol for thermal comfort outlined in [11]. Using the approach described in this paper it is possible to draw a cleaner picture of what the actual, real time, comfort level perceived within the building and the preferred conditions compared to the conditions prescribed by comfort standards are.

2. Methodology

The methodology followed for the determination of the Leaf Lab user preferences and satisfaction with internal conditions is based on ASHRAE's Performance Measurement Protocols for Commercial Buildings (PMP) [11]. The PMP is intended to provide "a standardized, consistent set of protocols, for a range of cost / accuracy that facilitate the appropriate comparison of the performance of six performance categories (energy, water, thermal comfort, indoor air quality [IAQ], lighting, and acoustics) in commercial buildings, while maintaining acceptable levels of building service for the occupants" [6].

This study involves the evaluation of thermal comfort at the intermediate level, using a combination of objective (monitoring of indoor comfort parameters and outdoor parameters) and subjective (Right-Now survey) methods.

Using the approach it is possible to draw a clearer picture of what is the actual, real time, comfort level perceived within the building. This analysis can prove to be very useful for the future optimal control of the thermal conditioning system. Knowing the actual thermal response, of both the building and the people occupying it, is even more important when addressing demand management strategies (DMS). To implement DMS it is first necessary to correctly evaluate the flexibility given by the thermal loads, quantifying the expected consumption of the building and the maximum deferrable amount from such baseline. Several works have been published on the topic, showing how historical data can be used to model HVAC systems. Having a baseline, the model can be used to predict the building thermal response to set point variations and, at the same time, the changes in terms of power consumption. Knowing the actual comfort limits, based on inhabitant's historical responses, would allow the development of models able to stretch the comfort conditions within a set of dynamic acceptable boundaries, increasing the building potential in terms of flexibility.

Subjective measurements are collected through an online questionnaire survey. The questionnaire survey is a "Right-Now" survey in which for each response the date and time is recorded and can therefore be compared against the concurrent monitored indoor environmental conditions.

The survey should be circulated for a sufficient number of days to enable the capture of the possible changes in thermal inertia of the building and comfort conditions during the day and during the week. For example in office buildings the preferred frequency of response is 3 times/day: morning (on arrival to the office), mid-day(after lunch) and afternoon (before leaving the office) and for a sufficient number of days to eliminate bias from non-standard internal or external conditions.

Objective measurements of indoor and outdoor environmental conditions are conducted with the help of sensors. The measurements give an indication of the conditions under which the HVAC system of the different monitored spaces operates. The positioning of the sensors should be made according to the guidelines set in EN 15251:2007 [9].

2.1. Matching and analysis of objective and subjective measurements

Through both measurement processes (objective and subjective) the measurement time is available. Therefore, it is possible to match the time that a response to the questionnaire is given with the monitored data. In addition, to the indoor environmental measurements, information on zone characteristics (i.e. floor area, floor level, orientation) that are known to have an impact on the thermal conditions of a space may also be collected with the help of a building survey.

3. Case study description

The methodology for the subjective and objective evaluation of thermal comfort is applied in the Loccioni Leaf Lab during the summer of 2016. The building is located in Angeli di Rosora, a rural area of the Ancona province in Italy (Figure 1.a). It is a two floors building consisting of many different spaces mainly: laboratories, warehouse, office spaces and meeting rooms. For this study the four main office spaces are considered: Research for Innovation, Energy, Industry and Progettazione.

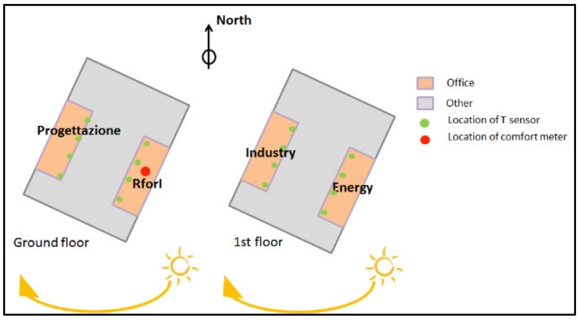

Figure. 1: a) Location of the Loccioni LeafLab b) Office spaces considered for the study and location of monitoring equipment

These office spaces are positioned perimetrically to the building. Research for Innovation and Energy have a South-East orientation while Industry and Progettazione have a North-West orientation (See Figure 1.b).

3.1. Objective measurements

The thermal environment monitoring is conducted with two different methods:

- Standard building monitoring system measurements (MyLeaf),
- Measurements with a portable comfort meter (Comfort Meter).

The MyLeaf monitoring system has been developed by the Loccioni Group and implemented in its own buildings. Data of monitored parameters are collected and are accessible through the MyLeaf web-based platform. The monitored environmental parameters useful for this analysis are Indoor Air Temperature (^{o}C) and Outdoor Air Temperature (^{o}C). Four Indoor Air Temperature sensors are located in each office space (see Figure 1.b); the measurement frequency is 15 minutes and all measurements can be downloaded from the MyLeaf platform in tabulated form (.csv).

Regarding the Comfort Meter, this is a portable monitoring device designed and developed by the Loccioni Group and the measurements provided are:

- Air velocity (m/s)
- Air temperature (^{o}C)
- Globe temperature (^{o}C)
- Radiant temperature (^{o}C)
- Relative Humidity (%)

A near sedentary activity is assumed (1.2 met) and light office wear (0.5 clo) for the Loccioni Leaf Lab office spaces. Setting these parameters, the Comfort Meter is capable of calculating the corresponding Predicted Mean Vote (PMV) and the Percentage of People Dissatisfied (PPD).

3.2. Subjective measurements

The minimum number of questions is selected for the Right-Now survey to limit the risk of survey fatigue. The following questions are selected:

- Zone. The office and laboratory zones are studied: Research for Innovation, Energy, Industry and Progettazione.
- Adjacency to external window (within 3 meters from the respondents' desk)
- Duration of time sitting at desk (<15 minutes, 5-15 minutes, >15 minutes)
- Thermal sensation. Vote on the ASHRAE 7-point thermal sensation scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot)
- Acceptability. It involves the thermal sensation reported in the previous question (Acceptable/Unacceptable).
- Preference. Statement of preference to change or not the thermal environment. Measured on a 3-point scale (1-warmer, 2-no change, 3-cooler).
- Gender. Male/Female.

The survey did not ask for humidity and radiant effects separately since they are perceived as temperature effects [1]. For this study, it is considered that the impact of thermal comfort on productivity is linked somehow to the level of acceptability/unacceptability. The age range of the Loccioni staff is not very broad (average age is 33-34 years), therefore a specific question is not included either.

4. Results

The study of thermal comfort in the Leaf Lab office spaces had a duration of eight calendar days (22/07-29/07/2016). The Right-Now survey is circulated in the six working days of the monitoring period. Overall, 214 survey responses are collected in this time. The highest number of respondents is recruited from the Research for Innovation (RforI) office space where the Comfort Meter is located. The objective and subjective measurements are matched based on studied office space and the time of measurement. Descriptive and multivariate analysis is conducted on the collected data.

Four out of seven questions of the Right-Now survey aimed at identifying the main characteristics of the respondents which could affect perceived thermal comfort. The aforementioned characteristics are summarized in

Table 1. As it can be noticed, fifty-one per cent of the respondents are from the RforI department to help support the more in depth study of the space with the Comfort Meter. From the other three departments the proportion of respondents out of total is between 15% (Energy) and 18% (Industry). In Progettazione the proportion of

respondents is 16%. The majority of respondents are male, sitting within 3 meters from an external window. Also, most of the respondents has been sitting at their desk for more than 15 minutes before taking the survey.

Table 1: Characteristics of study participants

		RforI	Energy	Industry	Progettazione	Total
Responses						
	Count	109	33	38	34	214
Gender						
	Male	54%	82%	92%	91%	71%
	Female	46%	18%	8%	9%	29%
Within 3 meters from external window						
	Yes	76%	79%	76%	68%	75%
	No	24%	21%	24%	32%	25%
Time sitting at desk						
	<15 min	9%	18%	8%	0%	9%
	5-15 min	19%	6%	11%	9%	14%
	>=15 min	72%	76%	81%	91%	77%

4.1. Objective and Subjective Analysis

In order to ensure that, concurrent Comfort Meter and survey responses are compared against each other. Only the time-matched measurements are considered in this section. Even by looking at concurrent Comfort Meter measurements and Right-Now survey responses, a discrepancy in thermal sensation is still observed (Figure 2). The plot reveals a trend for measured PMV votes to decrease as the day progresses, but they all remain very close or over +1. Such a trend is not observed for the subjective votes. Also, a large number of neutral votes is observed for the questionnaire measurements and even some slightly cool votes.

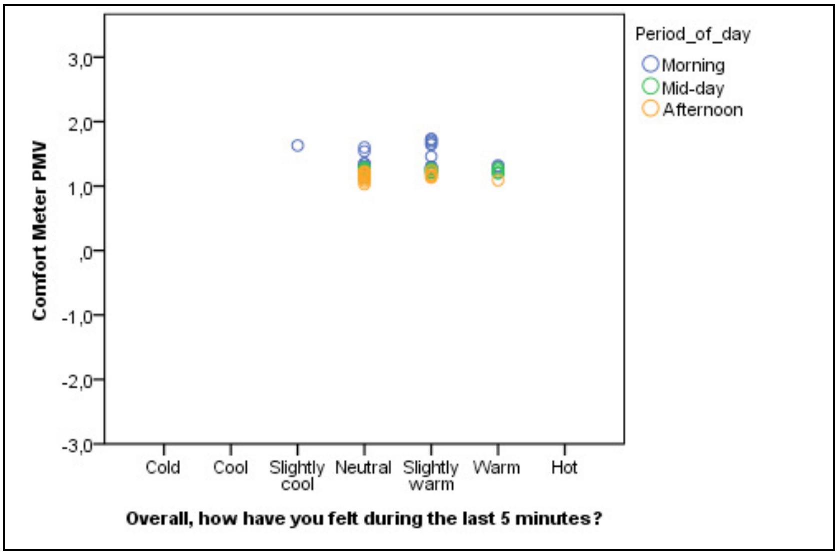

Figure 2: Objective and subjective concurrent measurements of thermal sensation (PMV)

The exact location of the respondents is not collected for the purposes of ensuring the anonymity of the respondents and also for reducing the length of the survey. Therefore it cannot be said for certain that the respondents feeling more cool or neutral are seated away from the Comfort Meter.

Still, the reasons for the discrepancy between the Comfort Meter measurements and the questionnaire survey findings should be investigated.

4.2. Determination of acceptable and unacceptable conditions

In this study dissatisfaction is considered to be the unacceptability with the thermal environment and the preference for change towards a cooler or warmer state. Average internal temperatures are grouped under these categories to help gain insight of the acceptable internal temperatures and the temperatures at which the occupants of the Loccioni LeafLab feel uncomfortable. The range of average internal temperatures for all studied zones separating between satisfactory and unsatisfactory conditions (see Figure 3).

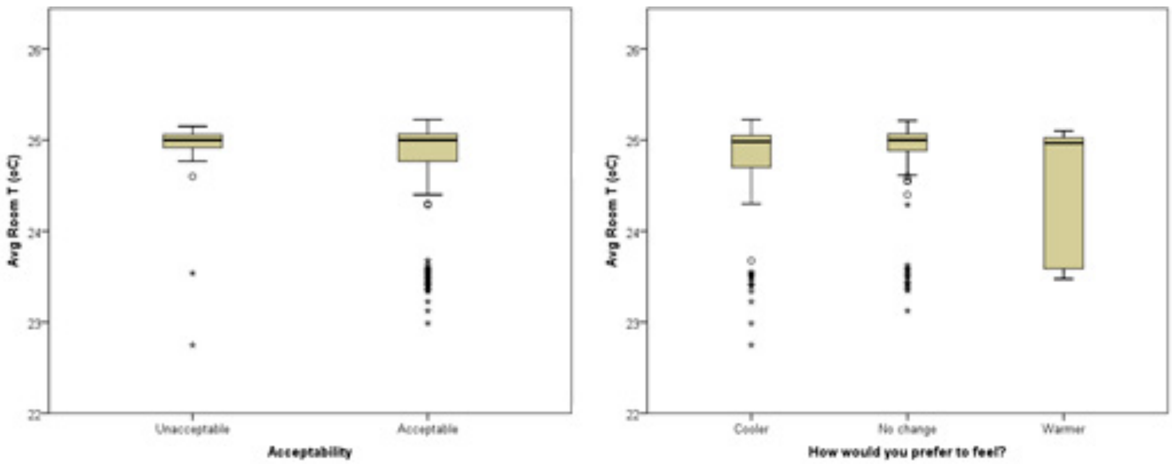

Figure 3: Boxplots with average internal temperature Vs a) acceptability and b) preference (MyLeaf measurements)

As observed through Figure 3 a) and Table 2, the mean acceptable temperature is only marginally lower than the unacceptable average temperature. In both cases the temperature is between 24.5 ^{o}C and 25 ^{o}C. However, the range of acceptable temperature is broader than the range of unacceptable temperatures and spans towards lower values.

Figure 3 b) and Table 3 again suggests similar temperatures between those that would prefer to change the thermal conditions and those that would prefer to keep the same thermal conditions. In fact, the average temperature that respondents are satisfied in is marginally higher than the temperature under which they would prefer to be cooler. Also, it is worth noting that the range of temperatures in which the respondents would prefer to feel warmer is much broader.

Table 2: Acceptable and unacceptable temperatures

	Average	**Std. Dev.**	**N**
Unacceptable	24.794	0.6102	19
Acceptable	24.728	0.5960	190

Table 3: Preferred temperatures

	Average	**Std. Dev.**	**N**
Cooler	24.693	0.6442	78
No change	24.790	0.5329	127
Warmer	24.385	0.7774	9

4.3. Leaf Lab Internal Comfort

The biggest proportion of respondents in all four spaces suggests neutral thermal sensation, however, a very large number of responses in RforI, Industry and Progettazione suggests a slightly warm thermal sensation as well. On the contrary, in the Energy department a large proportion of respondents is feeling slightly cool rather than slightly warm in many occasions. This is also reflected in the increased preference of the RforI, Industry and Progettazione for a cooler environment.

The most energy efficient way for satisfying the preference of respondents for a cooler environment would probably be through the increase in the air flow. Based on the Comfort Meter measurements there is room for enhancing air movement in the RforI department since the mean air speed in the space is found to be 0.004±0.0012 m/s.

The mean acceptable temperature is only marginally lower than the unacceptable mean temperature. In both cases the temperature is between 24.5-25°C. The mean temperature that respondents are satisfied in is marginally higher than the temperature under which they would prefer to be cooler. Again they are both between 24.5-25°C

5. **Conclusions**

This paper presents a methodology for the simultaneous subjective and objective evaluation of thermal comfort in commercial buildings. The methodology is based on the intermediate protocol level for the evaluation of thermal comfort as suggested by ASHRAE's Performance Measurement Protocols for Commercial Buildings. Using the approach described in this report, namely the matching and analysis of objective and subjective measurements, it is possible to draw a clearer picture of what is the actual, real time, comfort level perceived within the building. This analysis can prove to be very useful for the future optimal control of the thermal conditioning system.

The methodology is applied in the office spaces of the Loccioni Lead Lab, located in the province of Ancona, Italy, during the summer period. The objective measurements involved the monitoring of environmental conditions through the building monitoring system (MyLeaf system) and through a portable Comfort Meter. Subjective measurements is carried out with an online questionnaire survey (Right-Now survey) that is ansisd three times per day (morning, mid-day and afternoon). The study of thermal comfort in the Leaf Lab office spaces had a duration of 8 calendar days (22/07-29/07/2016). A total of 214 responses is collected with the Right-Now survey.

The objective and subjective measurements is matched based on studied office space and the time of measurement. Descriptive and multivariate analysis is conducted on the collected data. Overall, no significant thermal comfort issue is noted in any of the LeafLab office spaces. In all individual spaces the mean thermal sensation is found to be in agreement with the prescribed ASHRAE range of $-0.5 < PMV < +0.5$ and the requirement for <10 PPD.

The methodology presented in this paper can be utilized to assess the actual comfort range of the inhabitants of an office building, given a mixture of subjective and objective measurements. However, the results obtained in Loccioni's Leaf Lab lack significance due to the limited dataset of survey answers. Using a larger dataset it would be possible to assess the acceptable temperature range, per different time of the day, with a higher level of confidence. Regardless of their true significance, results can be taken into consideration when addressing the potential of such an approach if correctly integrated with the existing building management system. Knowing the actual, dynamic, comfort range would allow the BMS to optimize its schedule around it, minimizing both energy consumption and overall operational costs. Historical data on people response to different level of comfort can be leveraged to train a machine learning model that will be able to predict the future response to different comfort conditions. Such a model can be used to further optimize the HVAC control schedule, predicting for how long the HVAC system can be shutdown/partialized, based on the comfort level and the operating conditions, before producing discomfort for the inhabitants of the office. In other words, an accurate comfort response model, would allow the BMS to increase the amount of flexibility to be leveraged for demand response purposes. However, to properly train such a model, the dataset should be expanded including more samples from the Leaf Lab. In order to include more people in the study, while reducing the burden of completing the survey multiple times per day, a way to seamlessly integrate the survey mechanism in Leaf Lab's inhabitant workflow should be developed. Future studies will aim to expose the inhabitants of the Leaf Lab to the study for a longer period, in order to collect more critical data and confirm the potential of this approach.

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