Thermal comfort assessment in a sustainable designed office building

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ABSTRACT

Thermal comfort improvement at the lowest energy consumption is a key issue when dealing with sustainability in buildings. An appropriate passive design is mandatory under those circumstances. Prior to construction, simulation tools help to make designs more sustainable. However, it is recognized a gap between real performance and the predicted one. This article presents the comfort methodology applied in an office building located in the north of Spain, characterized by a continental Mediterranean climate. The edifice is constructed under the principles of the sustainability optimizing its energy performance. The thermal balance between indoors and outdoors and user behaviour shows the proximity of each office to the comfort bands. Warmer or colder set point temperatures correspond to higher energy demands. The application of the Fanger methodology produces high percentages of neutral sensation and low values of people dissatisfied, especially during the wintertime. In this period, warmer sensations increase the percentages of people dissatisfied.

KEYWORDS

Sustainability, comfort sensation, experimental monitoring, Fanger method

1 INTRODUCTION

Building sector represents a high percentage of the final energy consumption in European southern countries (Pérez-Lombard et al., 2008), particularly in Spain this percentage supposes about 31% (Eurostat, 2013). In order to reduce this energy consumption as well as the greenhouse gases emissions to the atmosphere, more efficient buildings must be constructed. The first stage of this objective is to design almost zero energy buildings. These buildings use natural resources in a passive way, which leads to a decrease in their energy demands (ARFRISOL, 2008). The second stage is to optimize the conditioning system, including renewable energies systems, to minimize their energy consumptions (GhaffarianHoseini et al., 2013). These energy reductions must not compromise thermal comfort sensation and healthy conditions.

Thermal comfort is defined as the human sensation of heat and cold for each climate conditions (Givoni, 1992), so it is quite difficult to quantify due to the high subjectivity involved. Factors such as climate, activity, age, metabolic rates, expectations or adaptability have a strong influence on the total calculation.

This article presents the comfort methodology applied in an office building constructed under the principles of the sustainability in the north of Spain during the summer 2014 and the winter 2015. The methodology applied is described in different phases (Soutullo et al., 2014). The first one analyses the temperature oscillations between indoors and outdoors and its distribution along the time. These analyses indicate the temperature gap and the associated deviation, giving an idea of how many "hourly degrees" are needed to achieve a hypothetical heating or cooling demand based on specific set points. To quantify how comfortable are these records, different bands have been established depending on the season of the year.

The second phase evaluates quantitatively the comfort sensation and the level of satisfaction reached inside the offices. The Fanger methodology (Fanger, 1967), has been applied for this study. This Standard proposes an iterative methodology that considered thermal balance, clothing characteristics and type and level of activity to predict the thermal sensation and the degree of discomfort of the people inside the room.

2 CLIMATIC REPRESENTATIVENESS

The office building studied is located in the north of Spain in Valladolid, characterized by a cold semi-arid climate. The latitude of the building is 41.65 N, the longitude is 4.76 W and the altitude is 735m. Comparing with the representativeness meteorological year (TMY) of AEMET (AEMET, 2015), during the summer 2014 higher values of solar radiation, softer extreme temperatures and less percentage of humidity have been registered. In the winter 2015 higher values of solar radiation, lower extreme temperatures and similar percentage of humidity have been obtained in comparison with the TMY.

2.1 Givoni chart

Analyzing with a Givoni Chart (Givoni, 1992), the hourly combination of the ambient air temperature and the humidity ratio measured along the summer 2014 and the winter 2015, the most representative passive and active techniques have been highlighted. As it can be seen in Figure 1, during the summer period there are many recorders inside the comfort band (orange zone), and two success have been detected. On one side, low temperatures especially in June and the first hours of July and August, demanded minimal heating. This could be supplied by internal loads to reach the comfort zone. On the other side, solar shadings, evaporative process, ventilation and refrigeration produced by internal thermal mass are needed to achieve the comfort band. The wintertime is cold and needs the combination of passive and active heating with conventional heating to reach the comfort zone.

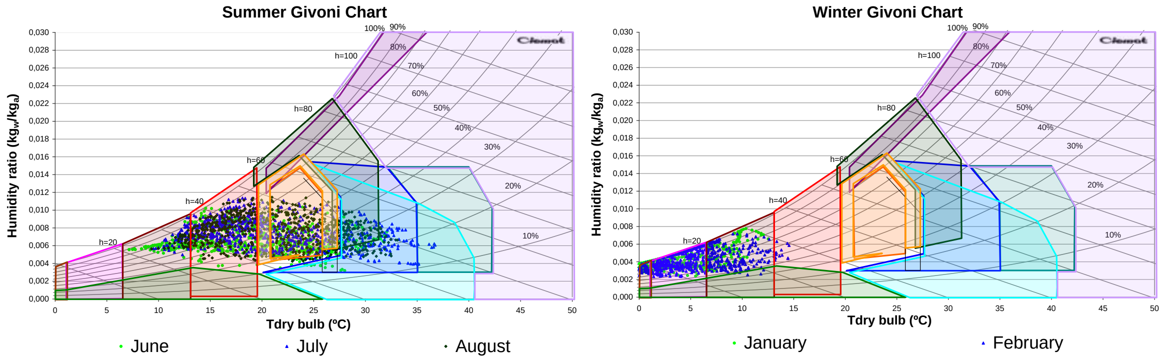

Figure 1: Summer and winter Givoni charts

2.2 Hourly cooling and heating degrees

The comfort set point temperatures for each band and the ambient measurements have been used to calculate the hourly heating and cooling degrees. When the ambient temperate is higher than the upper comfort limit, the difference between them is defined as cooling degrees. In the other side, if the ambient temperature is lower than the lowest comfort limit, the difference is defined as heating degrees. Applying this procedure, 9500ºC hourly heating degrees has been obtained during the winter 2015 with similar results in both months (January and February). This value points to cold winters. During summer 2014 and considering the ambient recorders, 934ºC hourly heating degrees and 2155ºC hourly cooling degrees have been obtained with warmer results in July and August. These values point to slightly hot summers.

As a relative humidity concerns, winter is a wet period with mean values that vary from 89% to 77% while summer is a temperate period with an average humidity of 51%.

3 BUILDING DESCRIPTION

The construction of this singular building has a usable floor area of approximately 1000 m^2 distributed across one floor. Main services developed in this building are administrative management, catering, gardening and retailing. The administrative area is divided at South orientation into closed offices.

3.1 Constructive information and systems description

Building materials used in this construction are green materials with low VOCs emissions. The edifice, constructed under bioclimatic criteria, is equipped with innovative active and passive systems. Different strategies were identified and integrated into the design of the building (Figure 2), optimizing its energy efficiency, improving the indoors thermal comfort and decreasing the CO_2 emissions. Most relevant strategies are: vegetation open areas under offices and a gardened roof, natural ventilation system composed by a grid system, and distributed lucernaires coupled to the air exchange system. Additionally, relevant spaces like a central atrium and a patio improve the thermal conditioning of surrounding and office areas, increasing natural light in winter and providing natural ventilation and solar protection to avoid overheating in summer.

Figure 2: Passive and active strategies. From left to right: gardened roof, lucernaire and central atrium

Moreover, façade design considers solar orientation. Southern façade is glazed to increase the direct solar gains within the offices, providing the use of natural light in winter. In summer, different shading devices and a ventilated façade reduce cooling loads (Figure 3). A solar absorption chiller provides pre-heated air to the air exchange system reducing thermal loads in summer.

Figure 3: From left to right: view of the South façade of the building and detail of solar absorption chiller

Energy loads are supplied by means of a combination of several renewable technologies, focusing on solar techniques. A 65 m^2 solar thermal system and an 87 KWp Photovoltaic system are installed on the roof. A vertical geothermal system with 77 KW cooling capacity and 101.5 KW direct heating system has been installed. Two biomass boilers using pellet fuels are installed: 244.5 KW for offices and 320 KW for industrial areas. A solar cooling system with a capacity of 4000 l and absorption refrigeration power of 264 KW has been installed.

3.2 Monitoring set-up

All relevant indoors and outdoors variables have been measured at an occupied building under real conditions. Monitoring is designed to evaluate the decrease in energy consumption and thermal comfort levels. The experimental campaign of this study has been done from June 2014 to February 2015. So the summer period comprises: June, July and August while the winter period includes: January and February. December must be excluded due to problems in the electrical fed of the acquisition system.

A 16-bit A/D resolution data acquisition system is used and modules distribution minimise wiring. Data are sampled every one second and one minute averages are recorded although other recording intervals are available. Time of all data provided will be in local time: this is Central European Time with daylight saving, i.e. in summer (UTC +2).

The location of all sensors will be done taken into account the special characteristics of the building in order to correctly evaluate the different representative areas. Across central areas from 3 to 6, closed office spaces are equally distributed. The two first offices are $12.5m^2$ while the east one is $17.6m^2$ (Figure 4).

Specific offices had been selected based on the occupancy level of the office, the characteristics of its construction and the implemented systems. Three representative offices have been selected for this study: Zn3_DC, Zn3_DO and Zn5_DE, belonging to central, west and east types respectively. The experimental measurements available in these monitored offices are: air temperature, relative humidity and CO_2 concentrations. Cooling and heating system performance is also monitoring.

Furthermore, outside boundary conditions are measured in a meteorological station installed on the roof of the building. South horizontal solar radiation, longwave radiation, air temperature, relative humidity, wind speed and direction and CO_2 concentration are the variables measured.

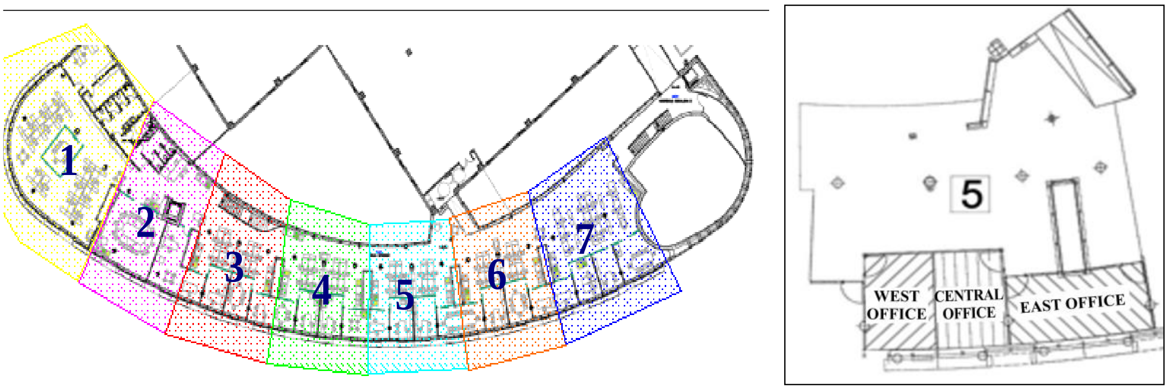

Figure 4: From left to right: Monitoring project design into seven areas, and detail of the office distribution on central areas.

4 COMFORT EVALUATION

The thermal balance reached inside the three offices studied has been evaluated by means of the temperature oscillations between indoor and outdoors as well as their comfort evaluation (Soutullo et al., 2014; Jimenez et al.,2013) To quantify how comfortable are these results during the whole year, two bands have been selected for each season. During summer period the comfort band is 24ºC ± 1ºC and during the winter period the comfort band is 22ºC ± 1ºC.

The energy demands of each office have been measured along the two periods, giving different values as a result of the user behaviour. In both periods heating and cooling demands are supplied. During the summer 2014, the cooling demands measured are: 19 kWh/m^2 in Zn3_DO, 12.7 kWh/m^2 in Zn3_DC and 0.3 kWh/m^2 in Zn5_DE, while the heating demands are always less than 1 kWh/m^2. During the winter months, the heating demands obtained are: 2.7 kWh/m^2 in Zn3_DO, 5 kWh/m^2 in Zn3_DC and 22.6 kWh/m^2 in Zn5_DE, while the cooling demands are always less than 1 kWh/m^2.

Taking into account that all the offices are faced to South and have similar use, the warmest behaviour is always registered in Zn5_DE while the coolest behaviour is registered in Zn3_DO.

4.1 Thermal characterization of building

Temperature oscillations produced by the climatic perturbations measured during the year 2014, allow the thermal characterization of the three studied rooms. The gap between these indoor temperatures and the comfort bands gives an idea of how efficient is this building. These offices have been performed from Monday to Friday, considering the occupational timetable from 7 am to 3 pm.

Figures 5 and 6 represent the frequency reached by the hourly mean temperature during the summer 2014 and the winter 2015 respectively in the three studied offices.

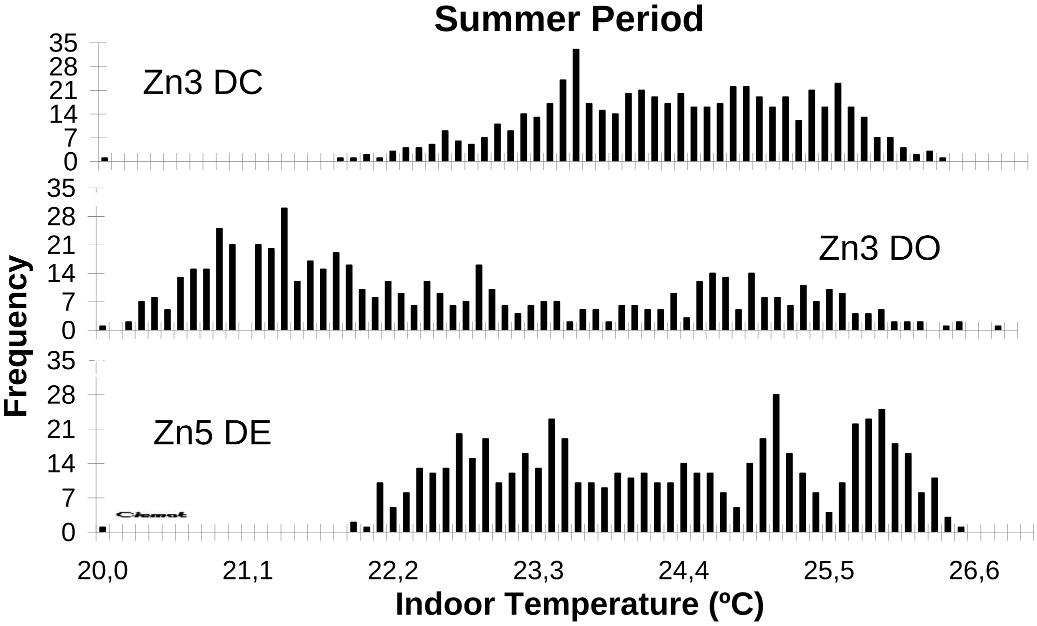

Figure 5: Indoor temperature histogram registered in the three studied offices during the summer 2014

During the summertime (Figure 5), the most frequent temperatures are: 23.6ºC in Zn3_DC, 21.4ºC in Zn3_DO, 25.1ºC in Zn5_DE. Considering the three levels established by the summer comfort band: <23ºC, 23º-25ºC and >25ºC, different percentages of occurrence have been obtained by each office and each level during these summer months (Table 1).

Table 1: Percentages of occurrence with the summer comfort temperatures

Office	Tª<23ºC (%)	23ºC<Tª<25ºC (%)	Tª>25ºC (%)
Zn3_DC	8	64	27
Zn3_DO	61	25	14
Zn5_DE	20	45	35

As it can be seen in Figure 6, the most frequent temperatures registered during winter are: 23.5ºC in Zn3_DC, 21.5ºC in Zn3_DO and 24.9ºC in Zn5_DE.

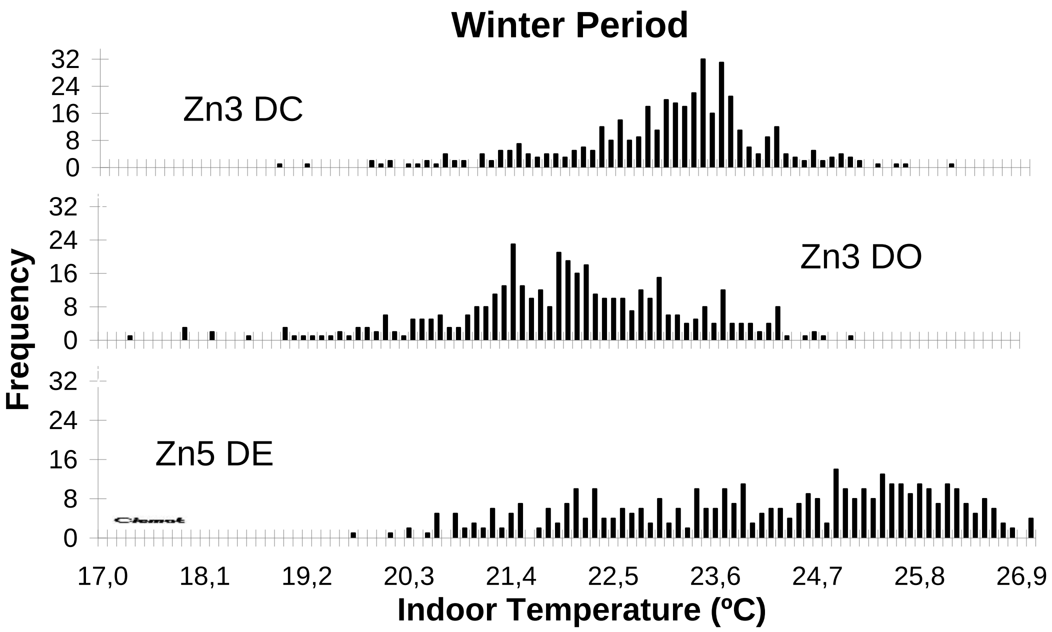

Figure 6: Indoor temperature histogram registered in the three studied offices during the winter 2015

Taking into account the three levels established by the winter comfort band: <21ºC, 21º-23ºC and >23ºC, different percentages of occurrence have been obtained by each office during these winter months (Table 2).

Table 2: Percentages of occurrence with the winter comfort temperatures

Office	Tª<21ºC (%)	21ºC<Tª<23ºC (%)	Tª>23ºC (%)
Zn3_DC	5	33	62
Zn3_DO	15	62	22
Zn5_DE	4	25	71

4.2 Heating or cooling degrees approach

Temperature differences between indoors and outdoors can represent the dynamic process that occurs inside each office. This balance shows the thermal gap distribution produced during a period of time. Both comfort bands (one for winter and one for summer) have been marked in these charts to quantify the results.

The limit comfort band temperatures have also been used to quantify the hourly effective heating and cooling degrees inside each office (method described in 2.2), giving an idea of how is the thermal deviation from the comfort scale established.

Figure 7 represents the hourly temperature drops measured inside Zn3_DC (red points), Zn3_DO (green points) and Zn5_DE (grey points) versus the ambient temperature during the summer 2014 and the winter 2015.

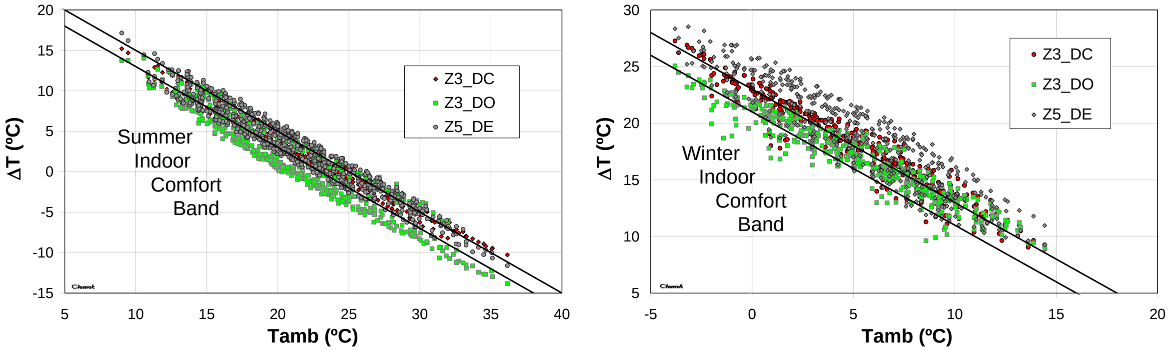

Figure 7: Thermal oscillation obtained inside the three studied offices during the summer 2014 and winter 2015

As it can be seen during the summer months the thermal dispersion from the comfort band has registered different behaviours, reaching the highest value in Zn3_DO (76%) and the lowest value in Zn3_DC (37%). In this period, the hourly heating degrees obtained in these offices are 51ºC in Zn3_DC, 571ºC in Zn3_DO and 87ºC in Zn5_DE while the hourly cooling degrees are 70ºC in Zn3_DC, 42ºC in Zn3_DO and 123ºC in Zn5_DE. The office Zn3_DO has been established lower set point temperature so higher energy demand is needed to reach this thermal condition.

During the winter months, the studied offices have reached high dispersion percentages from the comfort band, with the lowest value registered in Zn3_DO (40%) and the highest percentage in Zn5_DE (76%). The hourly heating degrees achieved in these offices are 13ºC in Zn3_DC, 67ºC in Zn3_DO and 8ºC in Zn5_DE while the hourly cooling degrees are 192ºC in Zn3_DC, 67ºC in Zn3_DO and 594C in Zn5_DE. These results show a warmest behaviour in Zn5_DE due to the highest set point temperature established by the user. This leads to an increase of the energy demand of this office as described in previous paragraphs.

4.1 Fanger thermal quantification

There are many processes that can quantify the indoor thermal comfort but the methodology recommended by the Spanish Building Code (Government of Spain, 2014) assumes the steady state conditions propose by the Fanger method, described by the International Standard ISO 7730 (ISO 7730, 1994).This Standard proposes a method to predict the thermal sensation and the degree of discomfort taking into account all the variables that influence the thermal exchanges between people and the environment. The comfort equation proposed by Fanger is a function of several parameters: meteorological variables, clothing characteristics and type and level of activity. As a result, two different indices can be obtained: the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied people (PPD). The first index predicts the hypothetical mean value of the thermal sensation obtained in the energy balance equation. This level varies between -3 and 3 and represents a thermal comfort scale from hot to cold environments. The centre of this 7-point thermal sensation scale is the comfort band that corresponds to zero energy balance or thermal equilibrium. The second index predicts the percentage of people dissatisfied with the environment conditions and varies between 5 and 100%.

Applying this iterative methodology to the office rooms studied, the PMV and PPD indices have been calculated for summer and winter period. Ambient conditions, low values of wind speed, sedentary activity and seasonal dress code have been considered as input values.

Figures 8 and 9 show the PMV values reached inside the three rooms during the summer 2014 and the winter 2015 respectively. In both figures a comfort band has been marked in grey to highlight the neutral sensation.

During the summer working hours the thermal sensation profiles achieved inside the three offices vary as a function of the user behaviour. The neutral sensation has reached percentages of 81.2% in Zn3_DC, 38% in Zn3_DO and 70.4% in Zn5_DE. To complete the thermal balance, slightly cool environments have been registered with percentages of 18.8% in Zn3_DC, 62% in Zn3_DO, 29.6% in Zn5_DE.

In wintertime both offices inside Zn3 have been achieved very high percentages of neutral comfort sensation, with values of about 94%. Slightly cool and slightly warm environments have also been obtained, with percentages that vary from 0.3 to 5.7% in Zn3_DC and 3.9 to 1.5% in Zn3_DO, respectively. However the comfort profiles registered inside the office Zn5_DE are different, with warmer values obtained during the hours of maximum solar irradiance. This effect is traduced to lower neutral sensation percentages (75.8%) and higher slightly warm percentages (24.2%).

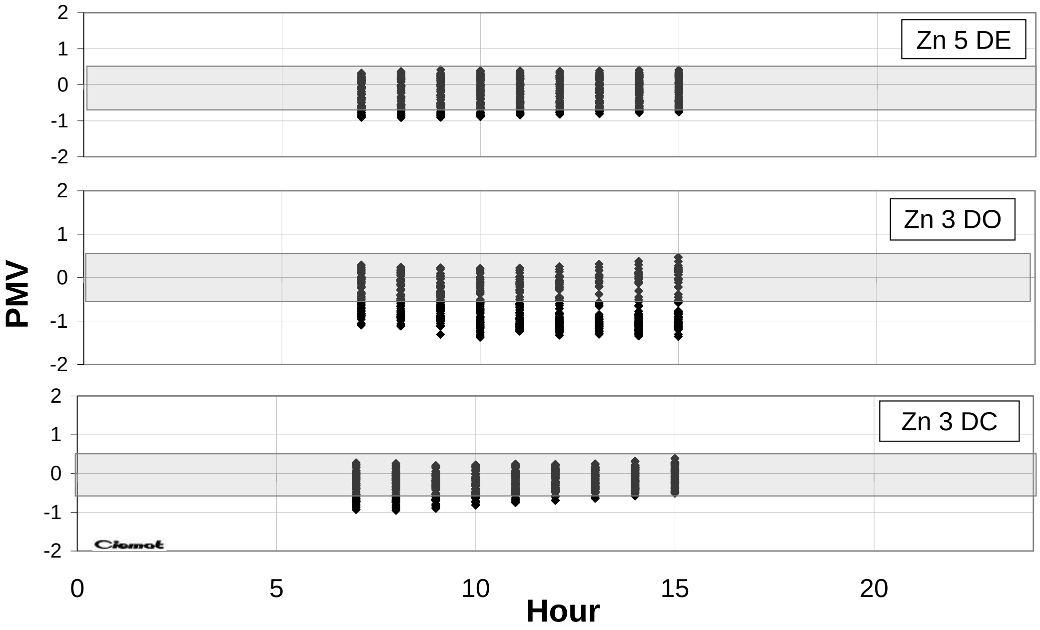

Figure 8: PMV index reached inside the three analyzed offices during the summer 2014

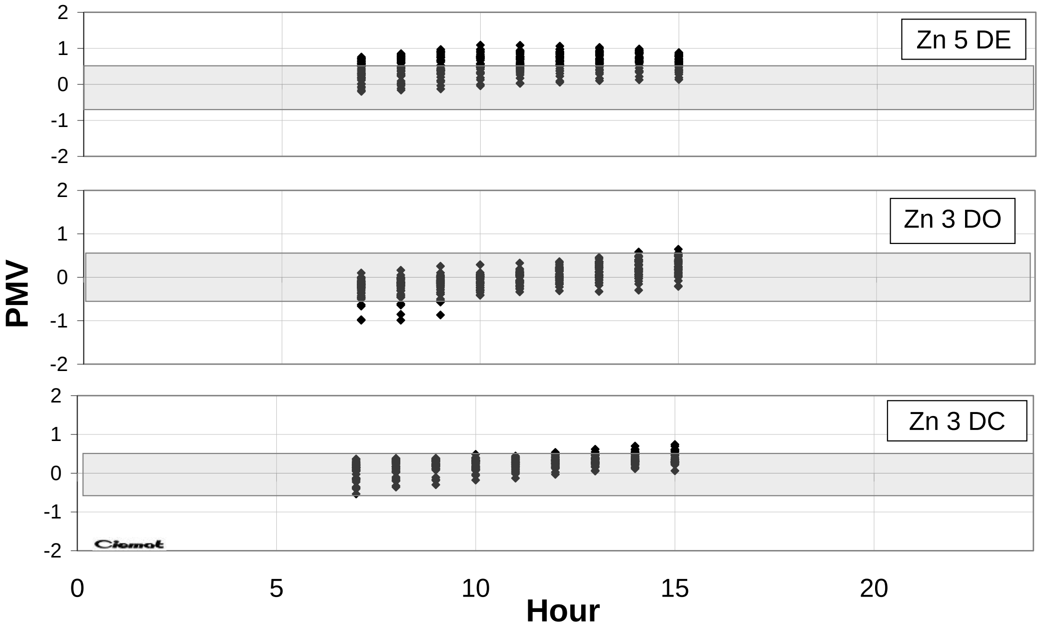

Figure 9: PMV index reached inside the three analyzed offices during the winter 2015

These thermal scales can be traduced in percentage of people dissatisfied with the environment, showing in the following figures as the PPD index (Figures 10 and 11).

As it can be seen, during the summertime the average profiles of people dissatisfied with the environment are similar inside Zn3_DC and Zn5_DE (mean value of 8.4%), growing to 18% inside the office Zn3_DO. The maximum percentages obtained oscillate between 24.2% in Zn3_DC, 44.2% in Zn3_DO and 22.5% in Zn5_DE.

In winter period the users are more dissatisfied in the office Zn5_DE and more comfortable inside both offices Zn3, with mean percentages that vary from 13.3 to 6.8% respectively. The maximum values registered oscillate between 30% in Zn5_DE, 25.7% in Zn3_DO and 16.5% in Zn3_DC.

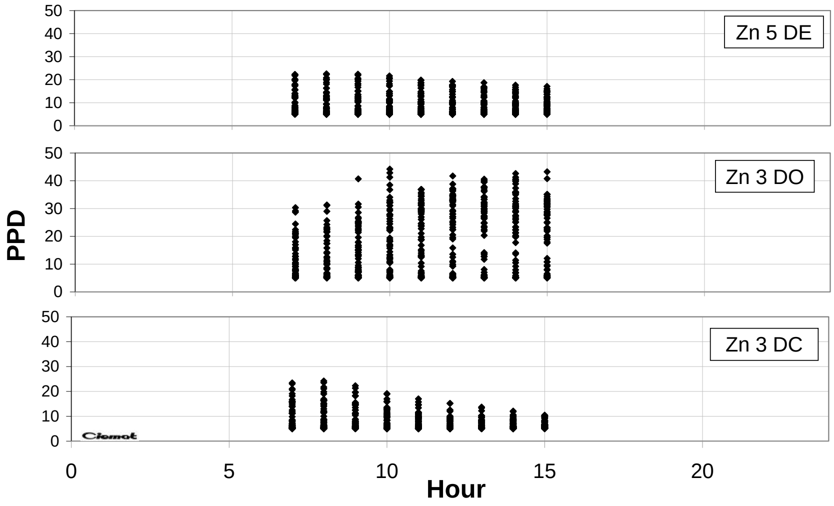

Figure 10: PPD index reached inside the three analyzed offices during the summer 2014

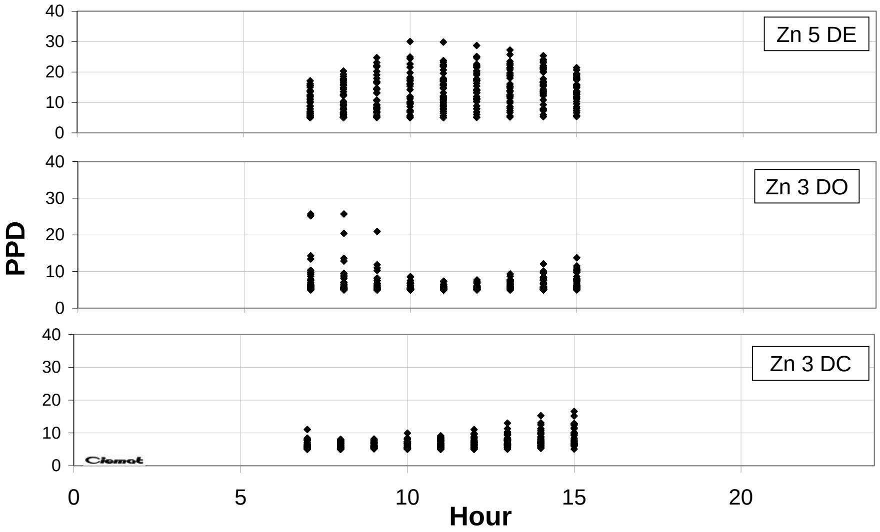

Figure 11: PPD index reached inside the three analyzed offices during the winter 2015

5 CONCLUSIONS

To evaluate the temperature profiles along the year, three office rooms have been monitored during the summer 2014 and winter 2015. The quantification of the thermal environment has been considering with two comfort bands: 23º-25ºC in summer and 21º-23ºC in winter. Taking into account these temperatures as set points, the percentages of occurrences within these bands have been calculated. Summer results show high frequency in Zn3_CD (64%), medium in Zn5_DE (45%) and low in Zn3_DO (25%). In winter the frequencies switch this trend to reach the highest value in Zn3_DO (62%) and low values in Zn3_DC and Zn5_DE.
Hourly heating and cooling degrees have been calculated considering the limits of these comfort references. These values point to low effective cooling degrees during the summer months in all the offices, but Zn3_DO needs medium effective heating degrees to achieve the comfort band. These results are corroborated by the energy measured which indicates that this office demanded more energy than the others. During the winter period low heating degrees are needed by all the offices but medium cooling degrees are demanded by Zn5_DE to reach the comfort band. This trend is corroborated by the energy measured in this office.

These results show different thermal profiles in each office depending on the user behaviour. Warmer or colder set point temperatures than the comfort bands correspond to higher energy demands.

Applying the Fanger methodology, high percentages of neutral sensation have been obtained in Zn3_DC and Zn5_DE (average 75%) decreasing to low percentages in Zn3_DO (38%) during the summer period. The PPD index shows that the colder behaviour of Zn3_DO increase the percentage of people dissatisfied (18%).

During the wintertime very high percentages of neutral sensation have been obtained in both Zn3 offices (higher than 90%) with low percentages of people dissatisfied (lower than 7.5%). In these months, the office Zn5_DE have been achieved warmer thermal sensations increasing and higher percentages of people dissatisfied with this environment (13.3%).

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