Thermal comfort and indoor air quality on end-user satisfaction level evaluation in a Nearly Zero Carbon neighbourhood

Julio Efrain Vaillant Rebollar [1,*], Eline Himpe [1], Arnold Janssens [1]

[1] Ghent University (NU), Ghent, Belgium

[*] *Corresponding email: julioefrain.vaillantrebollar@ugent.be*

SUMMARY
End-user satisfaction studies in residential buildings has to be approached combining the user's perspective and technical criteria to consider the complex interactions influencing the building energy performance. Therefore, in this study the physical characteristics of dwellings and their environments are assessed, user satisfaction is examined, and the relationship between them is investigated. The study aims to illustrate the end-user satisfaction in exemplary high performance buildings and to investigate how the users are interacting with these buildings. Examination of the building performance, thermal comfort and indoor air quality are the main focal points of the work. In general, results reflect a significant improvement on the satisfaction level of the inhabitants with the comfort of the dwelling after the refurbishment of the district. Findings from the cross-analysis of both surveys and measurements are used to further refine conclusions and identify the driving factors of the interrelationship between building performance and end-user satisfaction.

PRACTICAL IMPLICATIONS
Combination of user's perspective and technical criteria on buildings end-user satisfaction studies allows to consider the complex interactions influencing buildings energy performance.

KEYWORDS
End-user satisfaction level, Thermal comfort, Cross-analysis, Low energy buildings

1 INTRODUCTION
The main purpose of buildings is to provide a comfortable, healthy and secure indoor environment to the occupants. Therefore, alongside the economic impact of energy saving measures and refurbishment interventions, improvement of indoor environmental quality is a crucial subject. In this context, whether or not building performance fulfils the user expectation, can be explained by two causes: *a)* the failure of the building systems and *b)* the personal comfort appreciation of the users. As has been observed by several researchers, generally speaking, satisfaction is a subjective evaluation of the performance of products or services in meeting the needs and expectations of users or customers (Parker and Mathews,2001; Ueltschy et al.,2007). A review of related literature denotes that for the study of indoor environmental quality in buildings, the inhabitant's survey is one of the most common methods used to investigate the end user satisfaction from the perspective of the occupants. Besides, it is well known that efforts at incorporating the occupants' experience of the indoor climate, or the thermal environment analysis in a quantitative way are performed by use of the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD), based on the methodology developed by Fanger (1970). Regarding the same topic, Isaksson (2006) presented an interdisciplinary approach where qualitative interviews and physical measurements of the thermal environment were combined.

In the present work, different frameworks enabling quantitative and qualitative analyses, and different kinds of perceptions of the observed system have been combined. Consequently, in this study the physical characteristics of dwellings and their environments are assessed, user satisfaction is examined, and the relationship between the building characteristics and user satisfaction is investigated. Analysis of the building performance, thermal comfort and indoor air quality are the main focal points of the work. Findings from the cross-analysis of both the surveys and the measurements are used to further refine the conclusions, and identify the driving factors of the interrelationship of building performance and user satisfaction.

2 CASE-STUDY: NEARLY ZERO CARBON RESIDENTIAL COMMUNITY

The interpretation of the behaviour and questionnaire responses of the inhabitants has to take into account the previous situation of the community. Before the buildings refurbishment or replacement process carried out in the framework of the ECO-Life project, (TREN/FP7/239497/ "ECO-life"), the community was composed of a number of small building blocks with homogeneous architecture of around 163 semi-detached and terraced houses. The airtightness of the houses expressed in term of the air leakage rate at *50 Pa* was about $6,4\ h^{-1}$. In Belgium, the energy performance in the building sector is expressed by use of the "K-level" and "E-level" of the house. The K-level is a measure for the volumetric transmission heat loss coefficient of the house, the better the house is insulated, the lower will be the K-value. In this typical houses, the average U-value was *1,47 W/m²K* and the K-level was K103. The E-level or 'level of primary energy use', reflects the energy performance of the house. The average E-level of the old houses was E163. Notes that current standards for newly built houses is lower than E60 since 2014.

The physical characteristics of the buildings after the renovation or replacement to low-energy-standards have significantly improved. Currently, the community consist of 219 dwellings, differentiated in four groups based on their location, typology, construction approach and timing. The four multi-family buildings within the construction Phase 1 of the project are newly built in the south of the neighbourhood. Buildings A, B, C and D are multi-family buildings with 76 apartments with one, two or three bedrooms. The building envelope is highly insulated with special attention to the air tightness, leading to U-values somewhat about *0.15 W/m²K* and air leakage between *0.6* and *1* air changes per hour at a *50Pa* pressure difference (n50). The average E-level of the new houses is E25, and the average K-level of K20.

3 RESULTS AND DISCUSSION

Measurements campaign and data analysis

A measurements campaign including dwelling indoor temperature, CO2 concentration, ventilation flow rate, humidity as well as electricity use of the collective ventilation system have been conducted in the studied buildings. These measurements were carried out during the winter of 2013 - 2014. The four multi-family buildings are ventilated with three air handling units (AHU A, AHU B/C and AHU D). The ventilation flow rates are entirely controlled in the central air handling units. There is a constant flow rate for daytime (on average *200 m³/h/apartment*) and a fixed night set-back (on average *90 m³/h/apartment*). As was reported by Himpe (2015), in February 2014 the malfunctioning of a central air handling unit was discovered through the measurements of the ventilation flow rates in a sample of the dwellings. The results showed that in all these dwellings the flow rates were on average about 30% of the design flow rates. Inspection of the central air handling units revealed that they had been working continuously in the night set-back level, after acoustic complaints by the occupants. Subsequent acoustic measurements in the dwellings indicated that indeed the maximum allowed sound pressure level was significantly exceeded, e.g. measurements of *40 dB*(A) instead of the maximum allowed *30 dB*(A) in the bedrooms. The consequence of the reduced ventilation flow rates on the indoor air quality (IAQ) in the dwellings was investigated by use of CO2 measurements in some dwellings. A more detailed description and analysis of this subject was reported by Himpe (2015).

After installation of acoustic dampers on the main ventilation ducts of the dwellings, the settings of the AHU's were adapted, in order to allow them to provide the design flow rates during daytime. Figure 1 confirms that in August 2014, the failure was remediated and the ventilation supply air was preheated indeed. In the graphic the term *Fresh, Supply, Extract* and *Exhaust* are referred to the air temperature at inlet and outlet of the ventilation unit. In the figure it can also be identified that there is a constant flow rate for daytime (on average *200 m³/h/apartment*) and a fixed night set-back (on average *90 m³/h/apartment*). Consequently, the acoustic problem and the level of CO2 concentration were solved with the positive effect in the indoor climate improvement and the corresponding end user satisfaction.

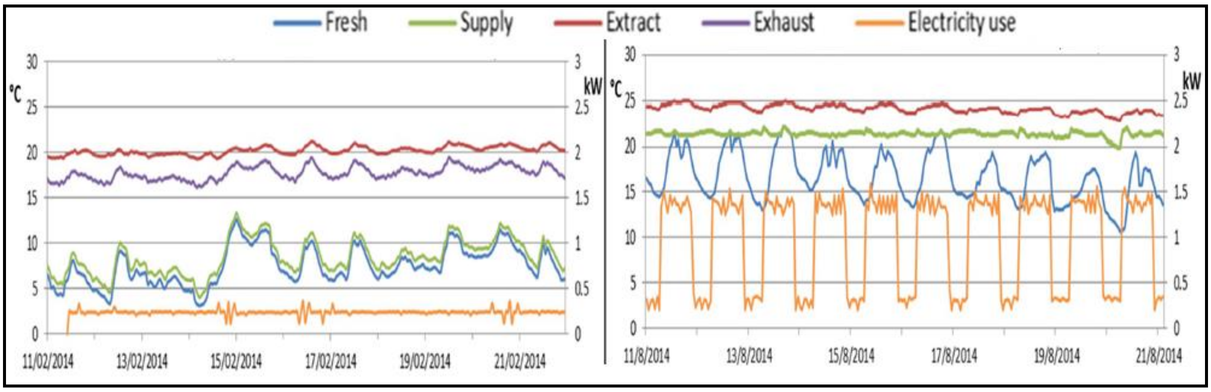


Figure 1. Parameters measured in AHU A in February and August 2014 (Himpe et al, 2015)

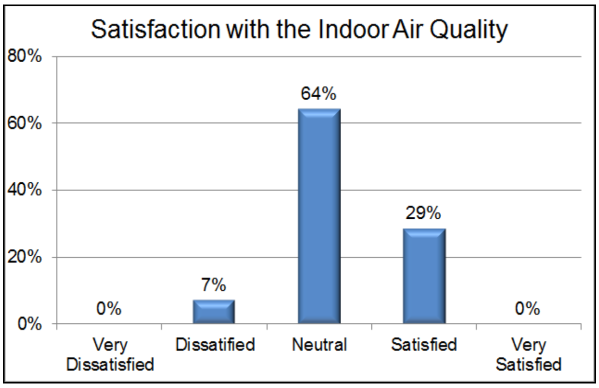
Ambient temperature, indoor temperature, relative humidity and absolute humidity in the apartments were measured during more than four weeks in the winter season of 2013 - 2014. The measurement interval of the acquired data was 5 minutes. Much of the occupied apartments present temperatures in the living room in the range of *20* and *25°C* with minimum and maximum of *18* and *27°C* respectively. Apartment A1.5 presents the higher value with average temperature above of the *25°C* as a result of the preference of the inhabitant to set a high set point temperature. The space heating circuit of the apartments have a radiator in the living room but also in the bathroom. In contrast with the temperature in the living room, regarding the temperature in the bathroom several apartments present values between *18* and *20 °C*. Although, in much of the apartments, the values of the median are in the range of *20* and *25°C* like in the case of the living room, the measurements in the bathroom present a larger variability in the results. In the bedroom, the range of temperatures are between *17* and *22°C*. In general there is no significant variability in the data except in the case of apartment C0.2. This apartment, C0.2, together with the apartment D1.4 presents the minimum value of *16°C* of temperature in the bedroom of the occupied apartments.

Analysis of the inhabitants survey

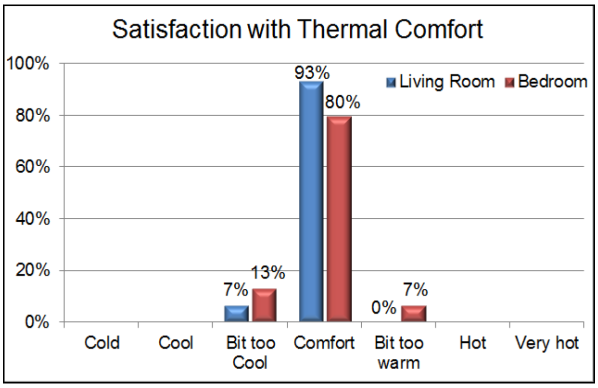
A sample of 15 (24%) apartments was selected from the total number of apartments of phase 1 that were occupied at the moment of the survey. The field survey was carried out during a period of four weeks after the measurement campaigns were completed, commencing from 1st

April 2014. A scale ranged from "-2" = very dissatisfied, "-1"=dissatisfied, "0"=neutral, "1"=satisfied and "2"=very satisfied, was used to measure respondents' level of satisfaction on several dwelling aspects. Survey results denote that there was negligible difference in the gender composition of the inhabitants. Most of the respondents (42%) were older than 65 years, while those who were between 45 years and 65 years old constitute 27% of the respondents; Also a large number of respondents (69%) are housekeeping or retired and spend a lot of their time at home. Result reflects that 73% of the respondents declare to define a set point temperature on average below the *21 °C*. 13% have reported set point temperatures in the range of *21°C* and *23°C*; while other 13% affirm to use set point temperatures higher than *24 °C*. It was found that only 13 % of the respondents declare to make some variation of the set point temperature during the day. Half of this, thus 6% of the total sample define a set point temperature of *27°C* during 12 hours of the day. This value represents the highest set point temperature defined by the whole sampled studied. The minimum value of set point temperature self-reported was *18°C* and it was defined by 20 % of the respondents. Later, a cross comparison between the self-reported set point temperature and the actual (measurements) hourly average indoor temperature will be presented.

The user self-reported comfort evaluation of the different dwelling aspects was also investigated. Similarly, the commitment with the environment and energy consciousness of the respondents was examined, as well. Results denote that 85% of the participants consider theirself as an environmentally committed person and an energy conscious person. It was also found that 92% of the participants declared to carry out self-control of lighting. However, the awareness regarding others energy carriers (electricity, water, heat) is in general lower than 70%. With respect to the respondents' satisfaction of the building services, i.e. ventilation system and heating system, according to the survey 48% of the respondents are satisfied with the ventilation system operation. A 9% are dissatisfied while 35% of respondents presents a neutral evaluation of the ventilation system operation. However when analyzing the result about the indoor air quality, the number of respondents which have a neutral evaluation about this topic increases. Figure 2 reflects that 64% of the participants give neutral evaluation while only 29 % have declared to be satisfied with indoor air quality.



a)



b)

Figure 2. Satisfaction level regarding a) indoor air quality and b) thermal comfort

Regarding thermal comfort more than 80% of the respondents have declared to feel comfortable both in the living room and in the bedroom. It can also be seen that 13% of the inhabitants reported that the bedroom is a bit to cool, while only 7% declare the same situation in the living room. Figure 3 gives an indication of the level of global satisfaction of the respondents before and after the refurbishment of the district. On the one hand before the refurbishment of the district results denote that 21% of the participants declared to be very dissatisfied with the comfort of the dwelling. Together with the 58% of the respondents which declared to be dissatisfied, results illustrate that more than 79% of the inhabitants were uncomfortable in their dwellings. 16% reported a neutral opinion regarding the overall comfort, while only 5% of the participants expressed to be satisfied with the overall comfort of the dwellings. On the other hand after the refurbishment of the district results denote that 46% of the participants have declared to be satisfied with the comfort of the dwelling. Together with the 31% of the respondents which have declared to be very satisfied, results illustrate that more than 75% of the inhabitants feel comfortable in their apartments. Only 23% have reported a neutral opinion regarding the overall comfort, while none of the participants have expressed dissatisfaction with the overall comfort of the apartments. In general results reflect a significant improvement on the satisfaction of the inhabitants with the comfort of the dwelling after the refurbishment of the district.

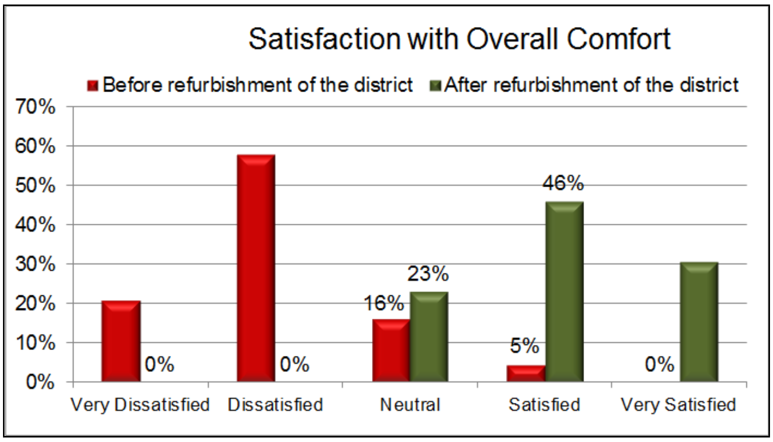


Figure 3. Subjective evaluation of the satisfaction level regarding overall comfort

Cross-analysis of measurements and surveys

In this section a cross analysis of survey results and measurement campaign is presented. We first present the cross-analysis regarding indoor temperature. Figure 4 displays the comparison of actual measurements of indoor temperature in the living room with the value of set point temperature declared by the inhabitants in the survey. In the graph the values defined as *Average* represent the mean value of temperature at a given hour of the day taking as a sample the 28 day of measurements campaign. *Tsetpoint* represents the values of set-point temperature reported by the respondents. In addition the upper and lower limit have been defined by means of the standard deviation at each hour. As can be seen in the apartment A 1.5 the inhabitant declared that during the night the set-point temperature is reduced till *23°C* while it is kept at *27 °C* during the day. Actual values denote that indoor temperature remains above of the *25 °C* during the whole day. Seventy per cent of the time or 17 hours of the day the temperature is somewhat around *26°C*. The standard deviation reflects a significant variability with values larger than *0.9°C* at each hour. With regard to apartment A3.2 there is *3°C* of difference between set point temperature declared in the survey and the actual indoor temperature. It can be seen also that there is a small standard deviation of about *0.2°C*. This small variability of the indoor temperature can partially be explained if the inhabitants effectively do not changes the set point temperature during the day.

In the case of apartment C 0.2 the actual value of temperature is always higher than expected according to the set point temperature reported by the inhabitants. However the difference in much of the hours of the day is lower than 1°C with respect to the average values. This difference tends to increase during the first hours of the morning up to *1.5°C*. The standard deviation was found to be somewhat between *0.8°C* and *1.1°C*. When analysing the rest of the apartments the results are in the same level of variability. In general it can be said that in much of the case it is difficult to find a good correlation between the declared set-point temperature and the actual values of indoor temperature. It should also be mentioned that several elements can influence the discrepancy of the results, for instance, a) difference of accuracy of the sensor and the thermostat; b) the position of the sensor which were placed somewhere else in the room, not near the thermostat; c) internal gains can play an important role; d) lack of heating capacity of the radiators, among others.

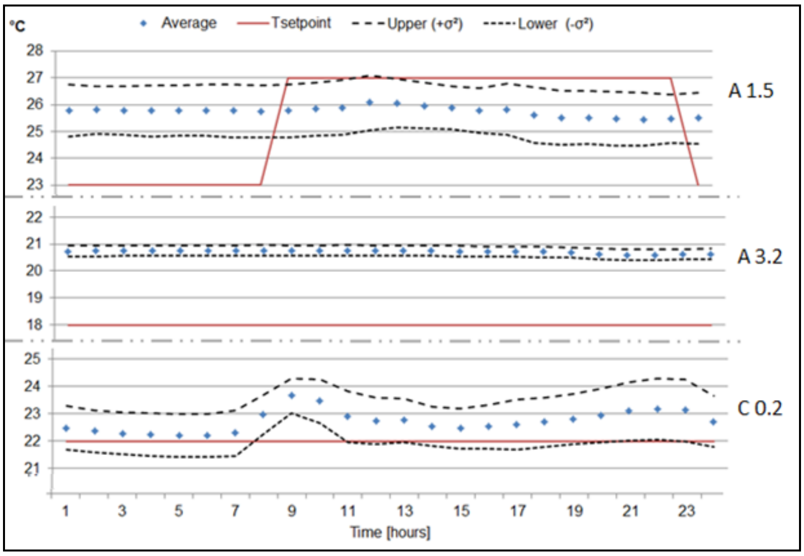


Figure 4. Measured indoor temperature in living room and declared set point temperature

In addition to the comparison of specific parameters like dwellings indoor temperature and set point temperature, the global subjective comfort evaluation of the inhabitant has also been considered. Therefore, an estimation of the well-known predicted mean vote, PMV index, has been carried out. The gathered data from the measurement campaign have been used to calculate the PMV value. The PMV scale is a seven-point thermal-sensation scale ranging from -3 (cold) to +3 (hot), where 0 represents the thermally neutral sensation. PMV index is determined considering air temperature, relative humidity, mean radiant temperature, air velocity, clothing thermal resistance, and a metabolic rate. An exhaustive description of the calculation method can be found in Fanger (1970). Figure 5 displays the estimation of the PMV index for a selected sample of apartments using the acquired data.

To address the estimation of the comfort level we ran a simple comfort calculation with TRNSYS software. For simplicity the TRNSYS simulation were conducted using a test facility geometry in which the similar indoor condition of the apartments were simulated. In addition a constant clothing factor of 0.5 and a metabolic rate of 1.2 met were used. As prescribe ASHRAE Standard 55 and ISO 7730, the metabolic rate allocated to subject sitting on the chair doing mild work was used. The histogram of figure 5 shows the number of hours during which the PMV value is included in a certain interval for each apartment of the selected sample. When the PMV value is between [-0,5 and 0,5] it is usually considered to be comfortable. In the graphics, we can see that in some of the apartments much of the time the PMV remains in the range of comfort between [-0,5 and 0,5], for instance, A1_7, A2_5, A3_2 and C0_3 . However, a small group of apartments presents comfort level divided partially in hours with good comfort but also with a number of hours where the comfort is reduced. This situation can be found in apartments A1_5, C0_2,C1_3, C1_6, and C1_7, which presents more than 20 % of hours in the range of [-0.5 and -1] or [0.5 and 1]. For readers interested in this topic a more comprehensive discussion of the results of the study can be found in Vaillant et al. (2015). Although the PMV have been estimated using major environmental variables (temperature and relative humidity) it should be noticed that these values may be different for different people corresponding to the same thermal environment. Moreover, a similar thermal environment can be differently perceived by the same person at different times.

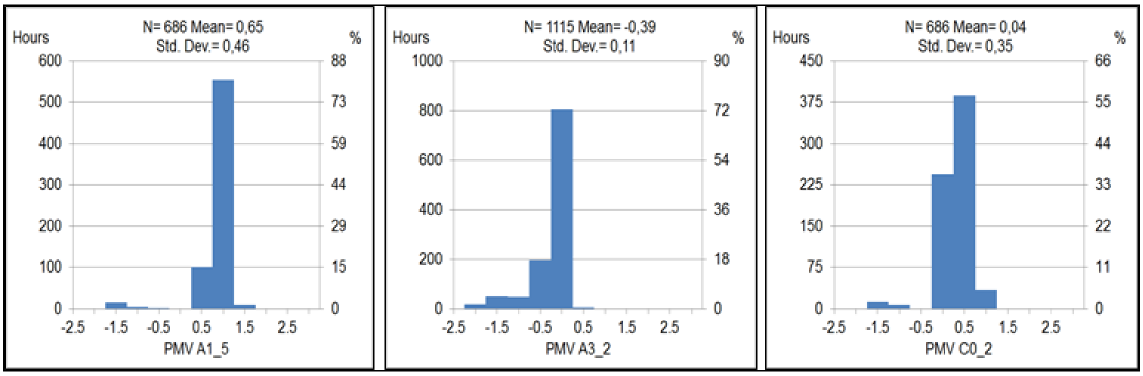


Figure 5. Estimation of the PMV index for the selected sample of apartments

A comparison of the PMV values for the same environmental conditions estimated with two different techniques is presented. As has been described in previous sections the level of comfort satisfaction has been calculated by means of measured of indoor environmental parameters (PMV Calc.) and derived by the subjective response method based on the 7 points sensation of the survey. Figure 6 displays for each of the selected apartments both mean PMV values i.e the calculated PMV values and the thermal comfort satisfaction reported by the respondents in the survey.

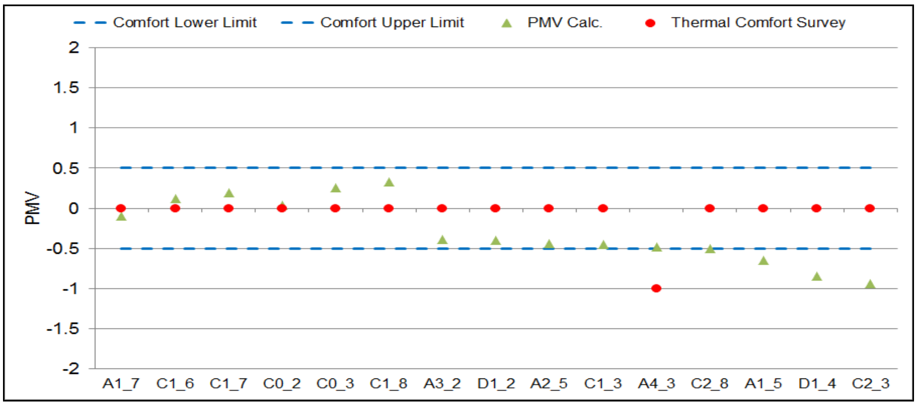


Figure 6. Comparison of PMV estimated from measurements data and Comfort survey

In few apartments, (A1_5, C2_3 and D1_4), the PMV estimated presents a negative result corresponding with a colder condition in contrast to the results reported by the respondents which was in much of the case within the range of good comfort. Although, the PMV calculation procedure using environment measured data does not take into account the adaptive nature of occupants, results denote that in much of the apartments this values are relatively close to the PMV values obtained using the subjective comfort evaluation from the survey. In general, it is assumed that the thermal sensation vote recorded during subjective survey are more close to reality. Nevertheless, it is recommended to use both approaches, i.e. information from survey and PMV calculation based on measurement of indoor condition to obtain a better overview of the thermal comfort of the study case.

4 CONCLUSIONS

The study assesses the physical characteristics of dwellings and their environments, examine user satisfaction, and investigate the relationship between the building characteristics and user satisfaction. As an example of user interaction with building performance, the malfunctioning of the central air handling unit detected during the commissioning process and the corresponding intervention to improve the problem have been illustrated. The main finding of a field survey in a sample of apartments within the ECO-Life project in Belgium (phase 1) have been presented. Results denote that 85% of the participants consider theirself as an environmental commitment person and an energy conscious person. According to the survey 90% are satisfied with the ventilation system operation. Regarding thermal comfort more than 80% of the respondents declared to feel comfortable both in the living room and in the bedroom. Results illustrate that more than 75% of the inhabitants feel comfortable in their apartments, declaring to be satisfied or very satisfied with the comfort of the dwelling. Furthermore, none of the participants have expressed dissatisfaction with the overall comfort of the apartments

A comparison of the PMV values for the same environmental conditions estimated with two different technique i.e. information from survey and PMV calculation based measurement of indoor conditions was presented. In three apartments the PMV estimated presents a negative result corresponding with a colder condition in contrast to the results of the survey which was in much of the cases within the range of good comfort. Although, in much of the selected apartments results are relatively close each other, it is recommended to use both approaches to obtain a better overview of the thermal comfort of the corresponding indoor environment.

ACKNOWLEDGEMENT

This study has been supported by CONCERTO project (TREN/FP7/239497/ “ECO-life”).

5 REFERENCES

Fanger P.O. 1970. *Thermal Comfort*. Copenhagen: Danish Technical Press. Denmark.

Himpe E. , Van de Putte S., Laverge J. and Janssens A. 2015. Operational performance of passive multi-family buildings: commissioning with regard to ventilation and indoor climate., *Procceding of 6th International Building Physics Conference, IBPC, Turin, Italy*. In *Energy Procedia*,Vol 78

Isaksson, C., Karlsson, F. 2006. Indoor climate in low-energy houses - an interdisciplinary investigation. *Building and Environment*, Vol 41, pp. 1678-1690

ISO ISO 7730. 1994. Moderate thermal environment - determination of PMV and PPD indices and specifications of the conditions for thermal comfort, *International Organization for Standardization*, Geneva.

Parker,C., Mathews B.P. 2001. Customer satisfaction: contrasting academic and consumers’ interpretations. *Marketing, Intelligence & Planning* , Vol. 19, pp 38–46.

Ueltschy,L.C.,Laroche,M.,Eggert,A.,Bindl,U.,2007.Service quality and satisfaction: an international comparison of professional services perceptions. *Journal of Services Marketing* Vol. 21(6), pp 410–423.

Vaillant Rebollar J., Himpe, E., Janssens A. 2015. ECO-life End-user satisfactory level Report BE: ECO-life Deliverable D.8.3.1. CONCERTO *ECO-Life Deliverables*. Ghent: Ghent University,. (TREN/FP7/239497/ “ECO-life”).