Detecting Comfort-based Climate Settings Using Surveys

Pablo Aparicio Ruiz, José Guadix Martín, Jesús Muñuzuri Sanz, Luis Onieva Giménez

Abstract— **It is possible to observe the users of a heating system's level of comfort through online surveys. Using fuzzy logic the behaviour patterns that generally occur in an office can be detected. It is also possible to detect situations when it can be decided to maximise comfort and/or maximise savings. This article puts forward a methodology for saving energy in these systems depending on the occupation and feeling of comfort of its occupants. The methodology used provides important and useful information to be able to select the comfort set-point of the rooms of a central heating system without the need to use fixed values based on programmed time schedules or any other methodology.**

Index Terms—**comfort, expert system, fuzzy logic, online surveys.**

I. INTRODUCTION

At present, thermal comfort tends to be analysed using models that follow the idea that these are applicable to all building types in the same manner. The patterns of these models are based on studies carried out on specific populations in a specific space. This happens in many research studies which focus on how to reach or maintain a room's temperature based on the PMV index (Predicted Mean Vote) [1]. Dounis [2] put forward a revised model of the existing advanced control systems based on energy saving and comfort management in buildings. The temperature controls are based on the PMV in most studies. However, many authors are critical of this [3].

These systems obviously need to have sufficient decision-making ability to be able to take action on the level of comfort while saving as much energy as possible. However, there are certain situations where maximising comfort must take precedence over maximising savings. Adjusting comfort in order to maximise savings may result in a lower quality of comfort; nevertheless, maximising comfort during a period of time to allow the users to adjust to the environment, waiting and then reducing it to values which

maximise savings may help improve the quality and acceptance of these savings. This will improve the building's energy efficiency along with a high level of acceptance from the users compared to the energy that is wasted in buildings at the moment.

In certain situations comfort should take precedence over energy saving as the users have to adapt to the changes in temperatures caused by the variations in the building's occupation, low body temperature at the beginning of the day [4], after breakfast and meals, etc. These all have an effect on human's thermal sensation and usually occur in conjunction with one another.

In 1997 the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) sponsored a research project [5] which studied comfort on a worldwide scale using a database. The results of this study caused the comfort levels of the ASHRAE standard to be revised significantly. They highlighted the potential for a reduction in energy needs by designing hybrid ventilation systems in many of the warm climate areas of the world [6].

Some studies have put forward neutral thermal conditions outside the ranges of comfort of the ASHRAE standard [7]. Whether the standard is accepted or not clearly depends on the place's weather and the building's conditions. Therefore, and without questioning the standard, comfort systems whose ventilation and air-conditioning is based on personalised comfort models must be developed.

There are many printed or internet-based studies that have surveyed the staff of many offices in different countries. The aim of these surveys was to obtain the staff's general level of comfort at the start or end of the day. An example is provided in [8].

These studies, that included many different types of buildings, used information on the physical characteristics of the buildings and the work spaces. However, comfort values associated with the room were not taken into account in these studies [9]. Other studies have focussed on workspaces, whether they are offices or factories, assessing the level of comfort with natural or artificial ventilation [10] as well as with air conditioning [11].

The response to comfort in an area of a building throughout the day can be seen in this study. The users were assessed using a standard set of key questions in order to measure the level of satisfaction with environmental factors.

II. ONLINE COMFORT SURVEY

The basic element for collecting data in this study was the survey. We used the international standard ISO 10551:1995 [12] which looks at the ergonomics of the thermal environment as a basis employing subjective judgement

scales. Even so, in spite of the requests of those surveyed, all systems m ust b e lim ited to c ertain norms whether determined b y the er gonomics ex pert o r b y t he l aws o r regulations of a country. T he s urvey w as p erformed us ing seven j udgement v alues: t hree b ased o n p ersonal thermal condition (perceptual an d em otional ev aluation an d temperature preferences), two based o n t he t hermal environment (personal acceptance an d t olerance) an d t wo based on emotional state (level of stress and w orker's mood). The information from the perceptual evaluation was used i n t he s ystem d eveloped. T he m ain questionnaire is shown in Table 1. The us ers filled o ut a s econd s urvey i n addition to these q uestions, w hich w as p erformed a t th e same time as t he f irst o ne. B oth s urveys w ere p erformed only o nce d uring t he d ay. The s econd s urvey contained questions which focussed on personal information, sex, age, height, weight and type of clothing.

TABLE I
MAIN QUESTIONNAIRE WITH SUBJECTIVE ANSWERS

Personal thermal condition

Perceptual evaluation	How do you feel just now?
	Hot, warm, slightly warm, neutral, slightly cool, cool, cold.
Emotional evaluation	How do you find the temperature right now?
	Clearly acceptable, acceptable, unacceptable, clearly unacceptable.
Temperature preference	How do you want the temperature to be?
	Higher, unchanged, lower.

Thermal environment

Personal acceptance	How do you find the air quality right now?
	Clearly acceptable, acceptable, unacceptable, clearly unacceptable.
Personal tolerance	How strong do you find the smell to be right now?
	No smell, weak smell, moderate smell, strong smell, very strong smell, overwhelming smell.

Emotional condition

Level of stress	The activity that you are carrying out... Is stressful, is normal, is relaxing.
Mood	At the moment you are...
	Happy, optimistic, excited, normal, uninterested, depressed, sad.

III. THE DESIGNS BASED ON FUZZY LOGIC

In many industrial applications, we can observe as the fuzzy logic is a tool based on the action. In case of comfort, the u sers p erform in tentional a ctions w hose m otivation i s only r eally k nown by them, and in directly b y th e s ystem. These motivations are known t hanks t o a questionnaire o f imprecise answers.

The main objective o f t he d esign i s to provide a reliable d etection s ystem b ut a t th e s ame tim e, an easy implementation. T his m ethodology pr oposal i s pu t into practice to try a system able to make decisions which are not based on the kno wledge of past actions as other techniques

such a s ne ural ne tworks c ould p rovide, but in a previous moment of the temporary space.

The s ituational p atterns s earch p ermit to obtain useful information in ta kes d ecision; th is suggests the use o f t he artificial intelligence te chniques. The fuzzy l ogic s tands out by its s implicity a nd e asy a pplication a nd is especially suitable for th e c ombination o f c hanges in demand v ery different f eatures. T his t echnique co nsists o f a series of general r ules (or d irectives), t herefore t he problem to be solved does not c orrespond u nivocally w ith a d etermined model of f uzzy logic, s o i s v ersatile as r egards to implementations and performance. Even so, as expected, all systems based on fuzzy logic present similar characteristics: They are r obust s ystems, th ey r equire little in formation input, a nd t heir p rocess u sually c onsists o n the f ollowing three p hases: f uzzification (conversion o f t he va lue o f t he input v ariables i n fuzzy v alues), p rocess of inference based on t he l ogics r ules; an d d efuzzification (conversion of the value of the fuzzy variables and decision making).

The rules applied in t he s ystems t hat u se t he f uzzy logic are approximated rules expressed by experts, since this is n ot a m ethodic modeling o f t he kno wledge of the fuzzy logic b ut is pr oposed out through the e xperience o f t he expert.

Nowadays ex ist a standard f or i mplementing f uzzy logic, e specially fuzzy co ntrol, cal led Fuzzy C ontrol Language (FLC) [13] that f acilitates th e d evelopment w ith APIs which allow implementation in different languages.

IV. METHOD

Through s ensors and t hanks t o t he c urrent technological tools (PCs, telephones, mobile phones, PDAs, etc.) the comfort users could be personalized and could be assessed, where and in which measurement. In addition, they can register the changes desired about the room states.

The o bjective o f t he m odel i s to p rovide a r eliable system with an easy implementation, hence the simplicity of the inputs required.

A. Parameter of design

t: Time p eriod af ter w hich an an alysis i s co mputed an d a subsequent d ecision i s m ade w ith r egard t o t he cl imate setting type.

B. Initial variables of the model

Ashrae (1997) [14] defines a range of assessments that could give a user: hot, warm, slightly warm, neutral, slightly cool, c ool and co ld temperature. T his r ange o f va lues i s extensive; s ome components take the same value as regards to the pattern that is wanted to search. Thus, we reduce this range to th ree c omponents: D issatisfied by heat, satisfied and di ssatisfied by c old. The following variables ar e defined:

-- v_{dh}, v_s, v_{dc}: Total valuation during t-period of the users. The ev aluation m ay b e: D issatisfied b y heat, satisfied and dissatisfied by cold.

-- v'_{dh}, v'_s, v'_{dc}: Variation of the total valuation between the t-period and the t-1 period.

-- o: The percentage of occupancy in the t-period.

-- o': Variation of occupation between the t-period and the t-1 period.

The va riations o f t he total v aluations d uring tw o consecutive different periods are calculated as follows:

$$v_\alpha{'}|_{\Delta t} = \frac{v_\alpha|_{\Delta t} - v_\alpha|_{\Delta t-1}}{v_\alpha|_{\Delta t-1}} \ with \ \forall \alpha \in \{dh, s, dc\} \qquad (1)$$

$$o'|_{\Delta t} = \frac{o|_{\Delta t} - o|_{\Delta t-1}}{o|_{\Delta t-1}} \qquad (2)$$

C. Conversion of the variables to fuzzy variables (fuzzification)

Depending o n the r elative p osition o f t he p reviously defined variables regarding to valuation expected during the interval, each v ariable i s d ivided, in percentage t erms, in three different components.

Thus, the valuations of the users during the t-period are represented and defined by three components, with regard to total number are concerned:

-- v_s, v_m, v_l: Component of set small, medium and large of the users, respectively.

As far as to variation is concerned, as much in negative sense a s p ositive, the number of u sers w ho v alue b etween two consecutive periods, also is divided into three parts or component p ercentages d epending o n t he s ign o f the variation between periods:

-- v'_n, v'_z, v'_p: Variation negative, zero and positive of the valuation, respectively.

The v ariables ar e r epresented b y t he ex act quantification o f t heir c omponent, a nd a re s hown i n the figures 1, 2 and 3.

In the figure 1, it is presented the membership function of comfort an d t he v ariation o f t his o ne. T he m embership consideration t o t he s mall g roup h as been underestimated and in medium group has b een d evaluated. T he r eason o f this change is that the users are not forced to indicate that are in a comfortable situation whereas use the system when they are d issatisfied. It can be o bserved t hat i f t hese ch anges would no t ha ve b een considered the system would gi ve the same value to the d issatisfied p eople th at to th e s atisfied people that have decided to respond.

Moreover, the t otal o ccupation o f us ers d uring t he t-period is r epresented by three co mponents t hat define it in terms of total quantity:

-- o_l, o_m, o_h: C omponent o f l ow, m edium and high occupancy, respectively.

With r espect t o t he v ariation (upward or downward) between t wo co nsecutive p eriods, each p arameter i s al so divided into three parts or component percentages depending on the sign of the change between periods:

-- o'_n, o'_z, o'_p: V ariation o f n egative, z ero a nd p ositive occupation, respectively.

The v ariables ar e r epresented b y t he ex act quantification of their component (see figure 4).
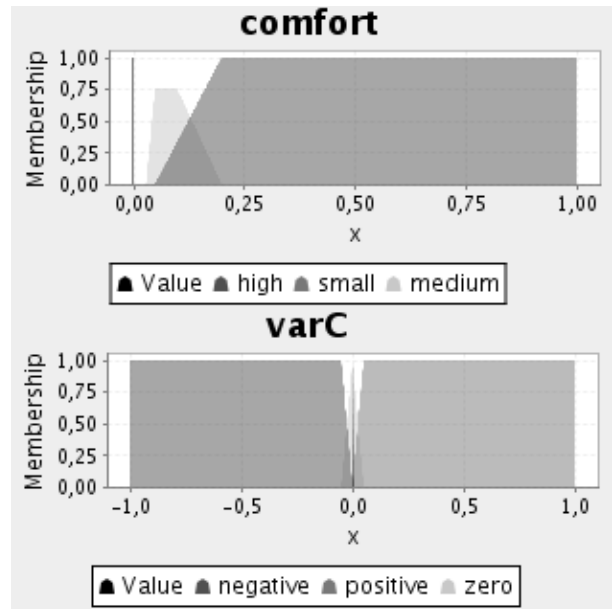

Fig. 1. Membership functions of comfort and its variation.
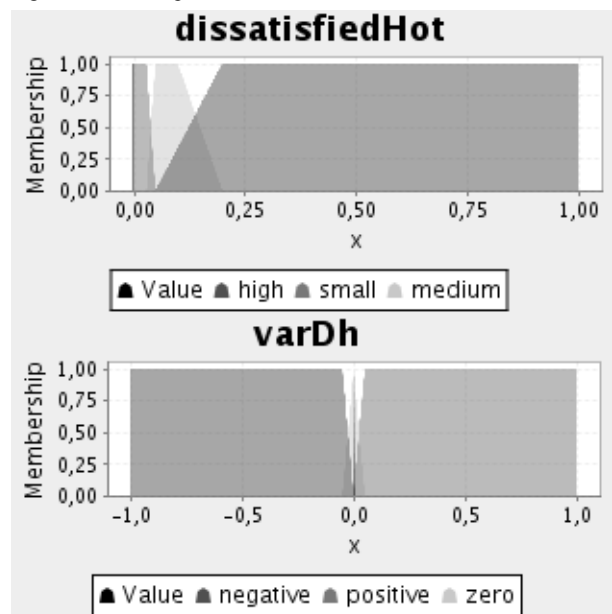

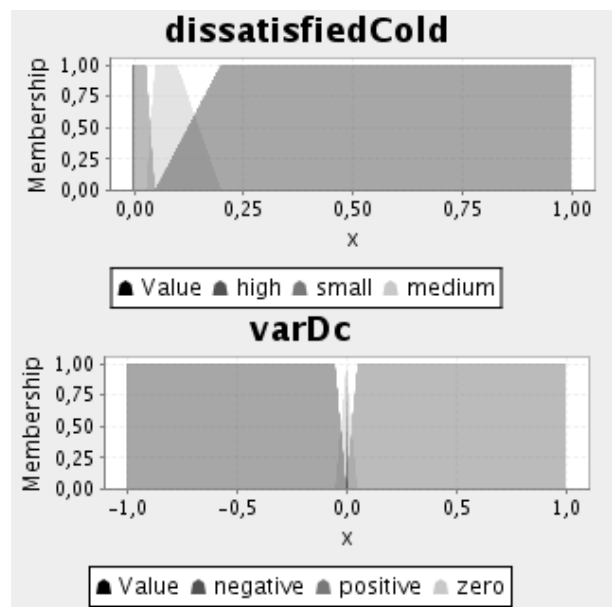Fig. 2. Membership functions of dissatisfied by heat and its variation.

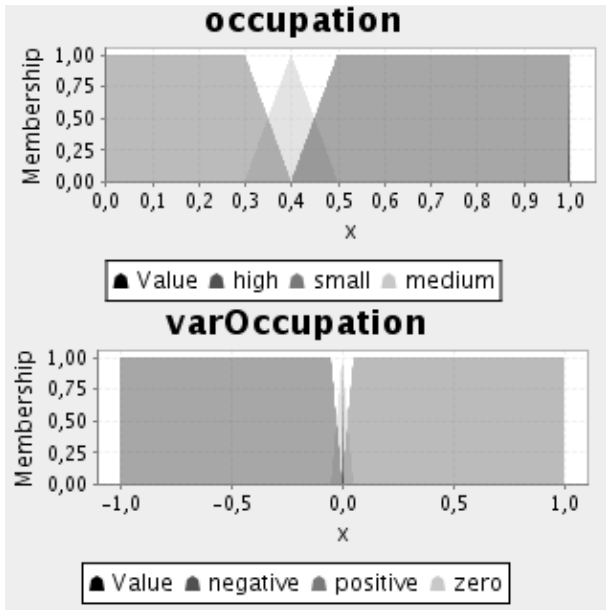Fig. 3. Membership functions of dissatisfied by cold and its variation.

Fig. 4. Membership functions of occupation and its variation.

D. Inference process based on fuzzy logic

Once t he t hree components of each v ariable are obtained, a set of logical rules is calculated considering the variation from the previous period:

$R1$: v_{hdh} && v'_{pdh} && o_h && o'_p then Out = comfort

$R2$: ...

...

The r ule R 1 in dicates the p reference t hat s hould b e given to the comfort if the occupation of the building is high, its variation is positive (the users are coming), the number of users d issatisfied by h eat is i ncreasing and i ts va riation is also p ositive. I n th is rule, t he l ogical && r epresents t he lowest among the four factors. T he m eaning of c omfort, neutral a nd s avings a re us ed t o s how t hat a s ignificant change in global l evel exists of co mfort and represents the configuration to which the system must give preference.

Once obtained the value for each rule, the force of the comfort, neutral and s aving c omponents are cal culated by applying o f th e r oot o f th e q uadratic s um o f a ll th e rules associated to each of them:

$$force_\alpha = \sqrt{\sum_i R_i^2} \quad \forall R_i \in \alpha \text{ with} \tag{3}$$

$$\forall \alpha \in \{comfort, neutral, saving\}$$

E. Converting of the value of fuzzy variables (defuzzification) and making decision

To m ake a d ecision ab out w hich demand that must prevail (the user comfort or saving into a ce ntral system), it is n ecessary t o t ransform t he p revious r esults o f the inference p rocess into a s ingle in terpretable r esult mathematically in the form of probability. A representative example of each of the forces is presented in figure 5. This is the r esult a fter g rowing a positive variation f or th e occupation to 3 1%, w hile th e evaluation f or comfort a nd warmth is maintained to zero, and valuations by dissatisfied by cold is increased in 6%, so that the rules give value 1 to comfort, 0.87 to neutral and 0'33 to saving.
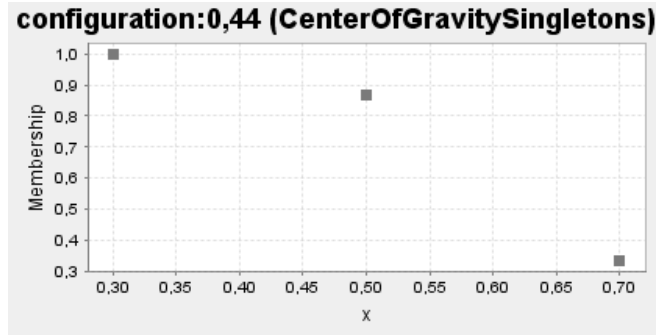

Fig. 5. Centers force.

Where 0 '3, 0 '5 an d 0 '7 r epresents, respectively, the "centers" membership functions o f Comfort (c), Neutral (n) and Saving (s) that are showed in figure 6.
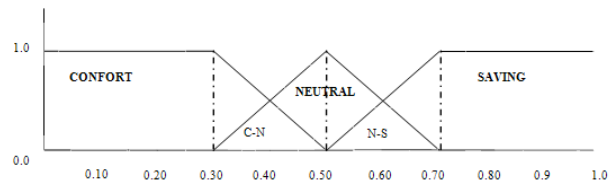

Fig. 6. Membership Functions.

Each center is weighted by respective component force (calculated earlier in the process of inference) and the average is calculated as follows:

$$weighting = \left(\begin{matrix} [C.center]\cdot[C.force]+ \\ [N.center]\cdot[N.force]+ \\ [S.center]\cdot[S.force] \end{matrix} \right) \Bigg/ \begin{matrix} [C.force]+ \\ [N.force]+ \\ [S.force] \end{matrix} \tag{4}$$

Figure 7 shows t he value s olution of t he output membership f unction f or t he c ase s hown in figure 5 . The center o f g ravity, associated t o t he b ehaviors t hat are defined, is o btained. In o ther w ords, the r eference p oint is shown with respect to the centers that represent the *Comfort*, *Neutral* or *Saving*. On this point, the behavior pattern in the analyzed p eriod is d educed. F urthermore, as n ot o nly the flow s ize is c onsidered b ut a lso th is variation in a period before, through the careful preparation of the rules, not only the pattern o f comfort can be d etected, b ut al so the e rror in next period can be predicted with a very s mall p robability. All th is, u sing a little amount of possible i nformation a nd due to temperature or the particularities of each user are not known. T he decision lo gics rules, in c ase that several types would b e d etected, the an swer would b e gi ven with gr eater probability value.
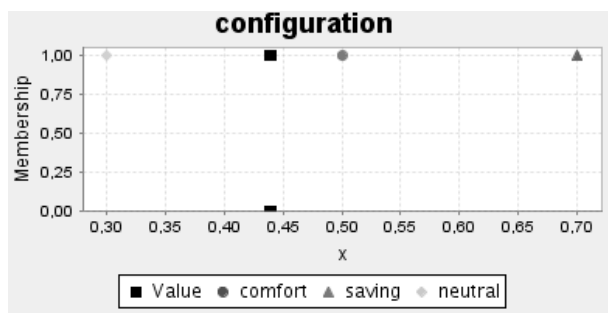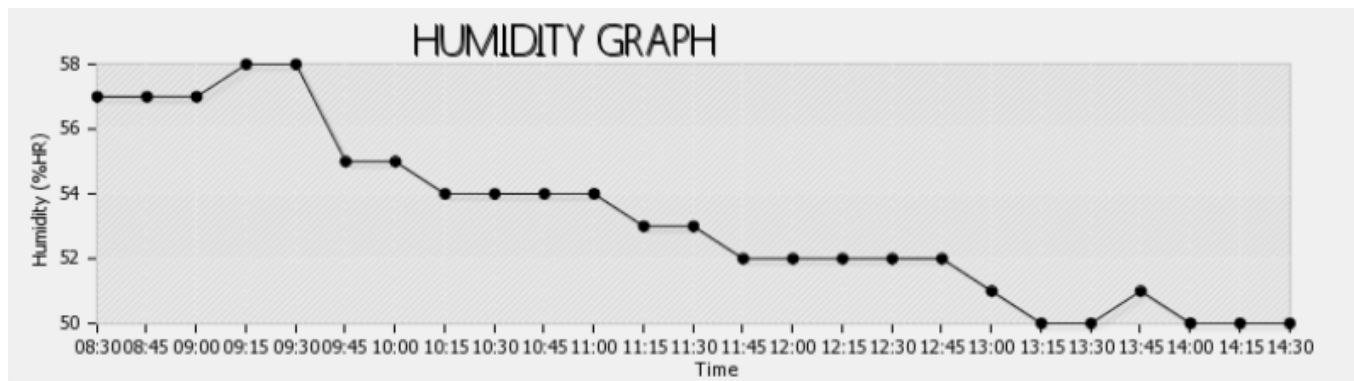

Fig. 7. Outputs.
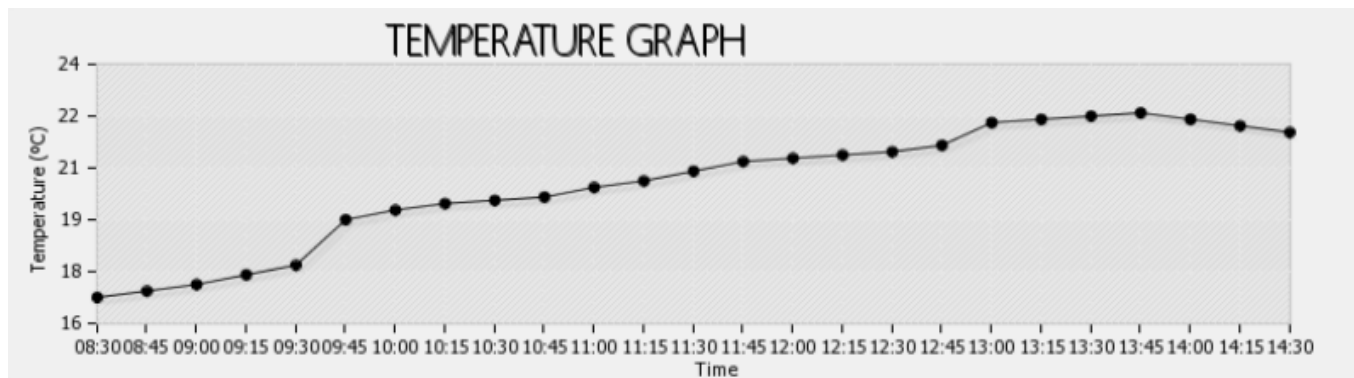
Fig. 8. Humidity of room A

Fig. 9. Temperature of room A

V. EXPERIMENT AND RESULTS

The previously explained model has been validated in one real case scenario. The experiment was performed on 20 December 2010 in two work spaces of the Higher Technical School of Engineering of the University of Seville. The study area was located on the second floor and no direct sunlight came through the windows due to the way it faced. It was, therefore, not very affected by the changes in the weather outside. The area analysed measured 78.37m². The area was heated by two fan-coil units which were part of a central heating system. For this experiment the study was performed with a single central heating system and the same temperature decision was taken for all the equipment of the different areas.

The area had 16 workspaces installed overall. The study was carried out between 8:30am and 2:30pm. The ages of the users studied ranged from 25 to 29 years old, who were all healthy and physically fit. On the whole, the users were wearing suit trousers, long-sleeve shirts, long-sleeve jumpers, thick socks and shoes. The outside conditions during the day remained between 9-13ºC and over 80% humidity. The temperature and relative humidity inside the work area was measured during the study, as can be seen in figures 7 and 8.

In addition to these measurements in the room, the users filled out an online questionnaire. The percentages of the answers to the first question by all those surveyed are shown in figure 10. It can be seen in the pie chart that not a single user stated that the temperature was hot during the study. Twenty-eight percent of the users stated that they felt comfort or neutral, 44% were uncomfortably cold and 28% were uncomfortably warm. Over the study only 4% of those surveyed stated that the temperature was low, while 56% wanted the temperature to be turned up.

With regard to the thermal environment, 20% of those surveyed considered the temperature to be unacceptable and 92% stated that the smell was weak or insignificant. As far as emotional condition was concerned, 20% of those surveyed believed that they were stressed, and the mood was always positive or normal.
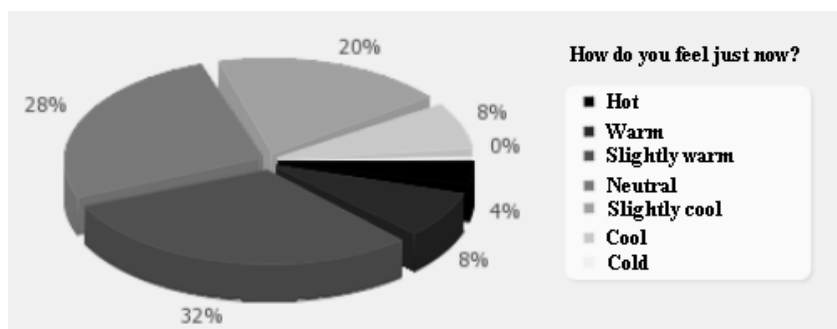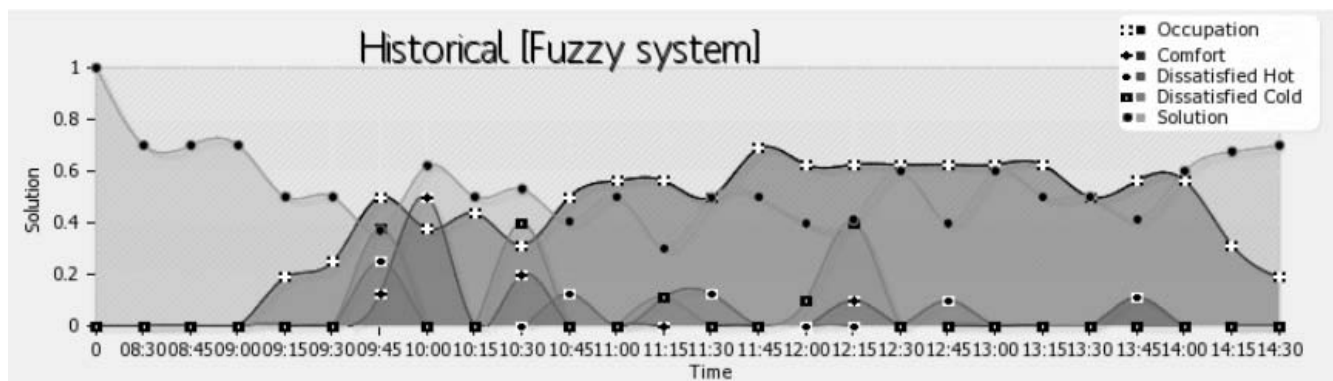

Fig. 10. User's answers

Fig. 11. Chronological results of the fuzzy-logic system

The answers to each question as well as the level of occupation are shown in figure 11. The solution's weighting is shown where a one represents maximise saving and a zero maximise comfort.

For these results to arise there needs to be very large difference between the answers. This may have happened at 9:45am. However, given that many users found the temperature acceptable, the request to maximise comfort was lower, meaning the need for this was decreased. However, moments when comfort took precedence were seen at 11:15am, 12:15pm and 12:45pm, compared to the beginning and end of the working day when the building occupation meant that the system tended clearly towards energy saving.

This system reflects the need to look for savings and comfort, although the tendency leant more towards comfort due to the high occupation of the space, which was modified according to the users' answers to the questionnaire.

VI. CONCLUSION

The methodology could be effectively used when it is not possible to carry out research into selecting the temperature value of the room based on the answers to the questionnaire and to the system.

The current experiment is not very significant due to the size of the sample studied. The study needs to be applied to a larger number of users in a greater number of rooms. An experiment which changes the period of time between the answers must also be performed.

The use of fixed climatic situations that are used today is not efficient. Future studies must take the users' needs into account in a dynamic way. Therefore, information systems that maximise energy efficiency must be researched taking the users' comfort into account based on the replies made at the time and based on models of users' comfort levels using surveys taken in the pass.

REFERENCES

[1] S. Soyguder, and H. Alli: An expert system for the humidity and temperature control in HVAC systems using ANFIS and optimization with Fuzzy Modeling Approach. *Energy and Buildings, 41,* 2009, pp. 814--822.

[2] A. Dounis, C. Caraiscos, Advanced control systems engineering for energy and comfort management in a building environment – A review. *Renewable and Sustainable Energy Reviews, 13,* 2009, pp. 1246--1261.

[3] J. Van Hoof, Forty years of Fanger's model of thermal comfort: Comfort for all? *Indoor Air, 18,* 2008, pp. 182--201.

[4] H. Almirall, and C. Marcet, Evolution of body temperature during the day, and chronotype growth function. Evolución de la temperatura corporal a lo largo del día, función de crecimiento y cronotipo. *Psicothermal, 7*(2), 1995, pp. 317--326.

[5] R. Dear, and G.S. Brager, Developing an Adaptive Model of Thermal Comfort and Preference. *ASHRAE Transactions, 104*(1), 1998, pp. 145--167.

[6] R. Dear, and G. Brager, The adaptive model of thermal comfort and energy conservation in the built environment.*International Journal of Biometeorology*, *45*(2), 2001, pp.100--108.

[7] D. Roonak, S. Kamaruzzaman, and M. Jalil, Thermal comfort in naturally ventilated office under varied opening arrangements: Objective and Subjective Approach. *European Journal of Scientific Research*, *26*(2), 2009, pp. 260--276.

[8] C. Huizenga, S. Abbaszadeh, L. Zagreus, and E. Arens, Air quality and thermal comfort in office buildings: results of a large indoor environmental quality survey. *Proceedings, Healthy Buildings, 3,* 2006, pp. 393--397.

[9] C. Huizenga, K. Laeser, and E. Arens, A web-based occupant satisfaction survey for benchmarking building quality. *Indoor Air*, 2002.

[10] S. Wijewardane, and M. Jayasinghe, Thermal comfort temperature range for factory workers in warm humid tropical climates. Renewable Energy ;*33*(9), 2008, pp. 2057--2063.

[11] F. Ellis, Thermal Comfort in Warm and Humid Atmospheres. Observations on Groups and Individuals in Singapore. *Journal of Hygene*, 51, 1953, pp. 386--404.

[12] ISO 10551, Ergonomics of the Thermal Environment: Assessment of the Influence of the Thermal Environment Using Subjective Judgement Scales, International Organization for Standardization, Geneva, 1995.

[13] IEC-TC65/WG-7/TF8: IEC 1131 Programable controllers. Part 7 : Fuzzy Control Programming. *International Technical Electronical Commission (IEC)*, 1997.

[14] Ashrae. Ashrae handbook-fundamentals – Atlanta. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1997.