New model for the search for comfort through surveys

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Abstract: - This paper presents a methodology used to provide important and useful information to select dynamically the comfort set-point of the rooms for a central heating system without using fixed values based on programmed time schedules or any other methodology. It is possible to observe the users comfort level of a Heating, Ventilation and Air-conditioning (HVAC) system through online surveys. Using fuzzy logic applied to the behaviour patterns that generally occur in an office it is possible to detect situations when it can be decided to maximise comfort and/or maximise savings. This methodology is designed to save energy in these systems depending on the occupation and comfort perception of its occupants.

Key-Words: - Comfort, fuzzy logic, decision support system, online surveys, evaluation, HVAC.

1 Introduction

The problem of select a value in the HVAC system when the user is in the same room as other users is a complex issue. Sometimes a unilateral decision or one imposed by force would therefore be unacceptable and causing in general the users to be insatisfied in their workspaces. As with democracy, the overall comfort is frustrated by particularism.

The survey approach is the best way to solve the problem, even though the evaluation process and their results are usually very difficult to analyze because of the vagueness and ambiguities surrounding the survey. For these reasons, there is a need to develop a model of confort evaluation that is:

- Quick, precise and produces results that might be easily analyzed.

- Allowing to get single-value score.

- Able to deal with the users' language.

Our objective is to implement a model based on the following principles:

- Users should not express the confort temperature by using numerical values.

- Users should be able to use a natural language to evaluate a set of characteristic features that significantly affect their comfort.

- The system should be quick with minimal mental load to permit focus on the interesting aspects of the evaluation.

Although the concept of fuzzy logic relies on age-old skills of human reasoning, the methodology of fuzzy logic is still young [1] and fuzzy systems is a relatively new field. Still, these systems have already demonstrated their ability to formalize in a computationally efficient manner the approximate reasoning capability typical of humans [2].

They are systems with a higher level of flexibility, autonomy and capability to work in dynamically changing and evolving environments, as is the case with the confort problem.

The application of fuzzy logic proved to be effective in significantly reducing total energy consumption compared with the conventional system [3], to meet the preferences of users [4] and improving PLC systems [5].

The problem modelling needs a system of modelling, control, prediction, classification and data processing. The system must be able to adapt and adjust its parameters, instead of using fixed values. That is, the system must be able to evolve and to self-evaluate.

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) [6]. Dounis [7] 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 [8].

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 [9], 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 [10] which studied comfort on a worldwide scale using a

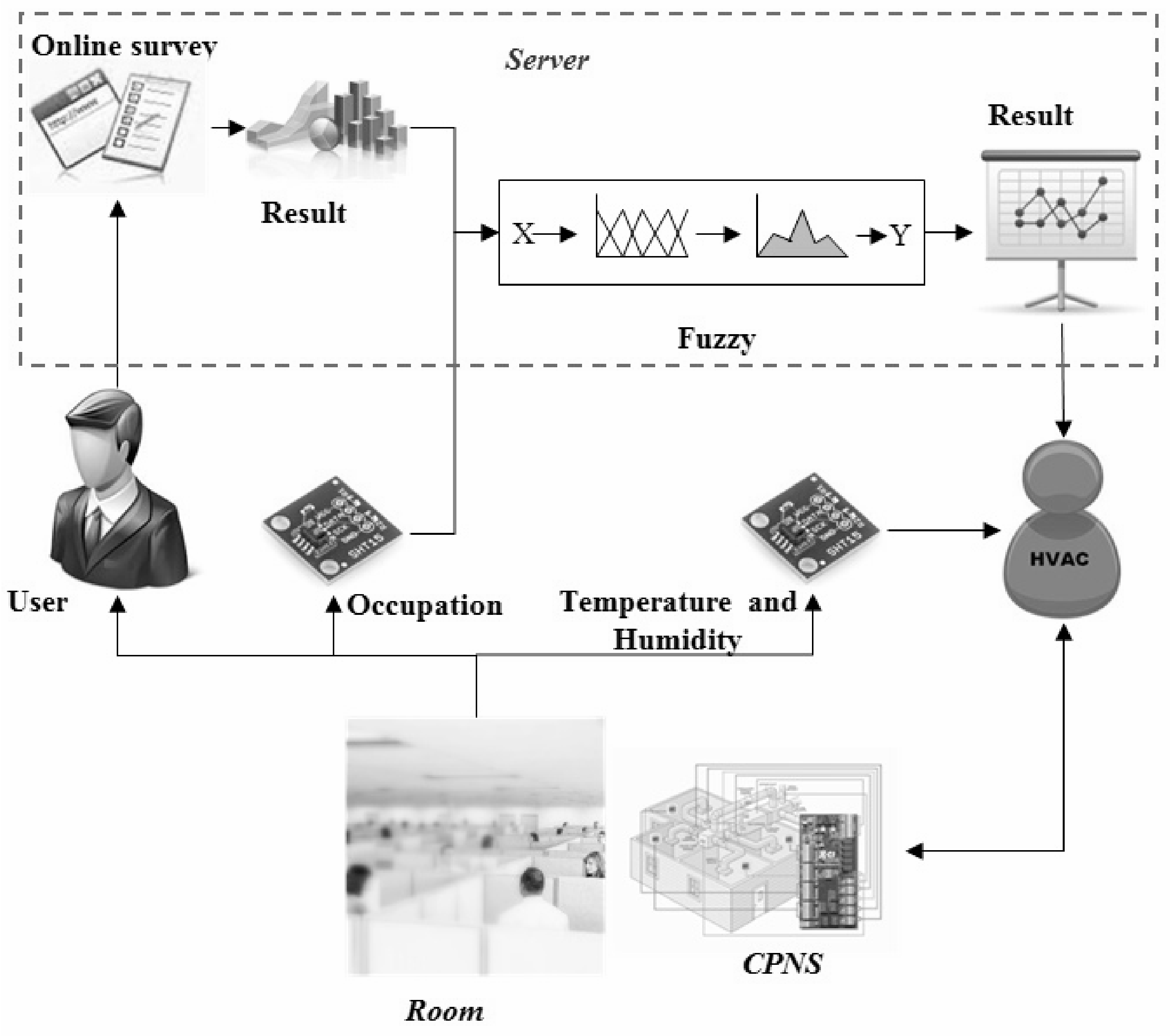

Fig. 1 The structure of the system.

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 [11].

Some studies have put forward neutral thermal conditions outside the ranges of comfort of the ASHRAE standard [12]. 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 [13].

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 [14]. Other studies have focussed on workspaces, whether they are offices or factories, assessing the level of comfort with natural or artificial ventilation [15] as well as with air conditioning [16].

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.

2 The structure of the system

In this section, we present the basic structure of the model or system that provides orientation information for selecting values in the HVAC systems. This is in any case a model that needs further development, but we will use it as a starting point.

Through Cyber-Physical Systems (CPSs) is combined the executive ability of the physical world (as the rooms status), and the intelligence of the cyber world (as the Fuzzy System) to add new capabilities to real-world physical systems.

Networked computing at multiple scales in systems that use computation, communication and interacting with physical processes, s in this case, could be useful applied the Cyber-Physical Networking Systems (CPNSs) that consist of computational and physical elements integrated towards specific tasks [17][18]. Generally, both data and systems in CPNSs are heterogeneous [19]. For this task that is required one common mechanism for rapid implementation, for example, smartphone-based mobile cyber physical system nodes utilizes the network connectivity to link the mobile system with either a server or a cloud environment, enabling complex processing tasks. Common applications of CPS typically fall under sensor-based systems and autonomous systems. This system combines distributed sensing (each room is equipped with a sensor node monitoring its status), navigation, manipulation and wireless networking. The rise in popularity of smartphones has increased interest in the area of mobile cyber physical systems; the smartphones allow answering online comfort surveys.

Figure 1 shows a diagram that represents the structure of the system to apply this methodology, for example with a smart phone connected to a network. The system uses as inputs the occupation, temperature and humidity, these devices are networked to a server. A server stores the results of the surveys, which are read by the fuzzy logic system in each time period. The results of the fuzzy logic system and current data on the HVAC system provide information to search for the best values for each room.

3 Online comfort survey

The basic element for collecting data in this study was the survey. We used the international standard ISO 10551:1995 [20] 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 must be limited to certain norms whether determined by the ergonomics expert or by the laws or regulations of a country. The survey was performed using seven judgement values: three based on personal thermal condition (perceptual and emotional evaluation and temperature preferences), two based on the thermal environment (personal acceptance and tolerance) and two based on emotional state (level of stress and worker's mood). The information from the perceptual evaluation was used in the system developed.

The main questionnaire is shown in Table 1. The users filled out a second survey in addition to these questions, which was performed at the same time as the first one. Both surveys were performed only once during the day. The second survey contained questions which focussed on personal information, sex, age, height, weight and type of clothing.

Table 1: 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.

4 The designs based on fuzzy logic

As stated by Irvin W. Kay [21], Fuzzy logic may be useful in the following circumstances:

- When a human observer supplies data that is subjective or is coded in imprecise language, as a survey.

- When mathematically precise algorithms are too complicated or otherwise inappropriate.

- When it is desirable to model ordinary human behavior, as human comfort.

- When it is necessary to deal with concepts that cannot be measured but must be compared in a logically consistent way, as general comfort.

The literature concerned with fuzzy methodology now includes many articles [2,22,23,24] and has even developed tools for learning [25]. In many industrial applications, we can observe as the fuzzy logic is a tool based on the action. In case of comfort, the users perform intentional actions whose motivation is only really known by them, and indirectly by the system. These motivations are known thanks to a questionnaire of imprecise answers.

The main objective of the design is to provide a reliable detection system but at the same time, an easy implementation. This methodology proposal is put into practice to try a system able to make decisions which are not based on the knowledge of past actions as other techniques such as neural networks could provide, but in a previous moment of the temporary space.

The situational patterns search permit to obtain useful information in takes decision; this suggests the use of the artificial intelligence techniques. The fuzzy logic stands out by its simplicity and easy application and is especially suitable for the combination of changes in demand very different features. This technique consists of a series of general rules (or directives), therefore the problem to be solved does not correspond univocally with a determined model of fuzzy logic, so is versatile as regards to implementations and performance. Even so, as expected, all systems based on fuzzy logic present similar characteristics: They are robust systems, they require little information input, and their process usually consists on the following three phases (figure 2): fuzzification (conversion of the value of the input variables in fuzzy values), process of inference based on the logics rules; and defuzzification (conversion of the value of the fuzzy variables and decision making).

The rules applied in the systems that use the fuzzy logic are approximated rules expressed by experts, since this is not a methodic modeling of the knowledge of the fuzzy logic but is proposed out through the experience of the expert.

Nowadays exist a standard for implementing fuzzy logic, especially fuzzy control, called Fuzzy Control Language (FLC) [26] that facilitates the development with APIs which allow implementation in different languages.

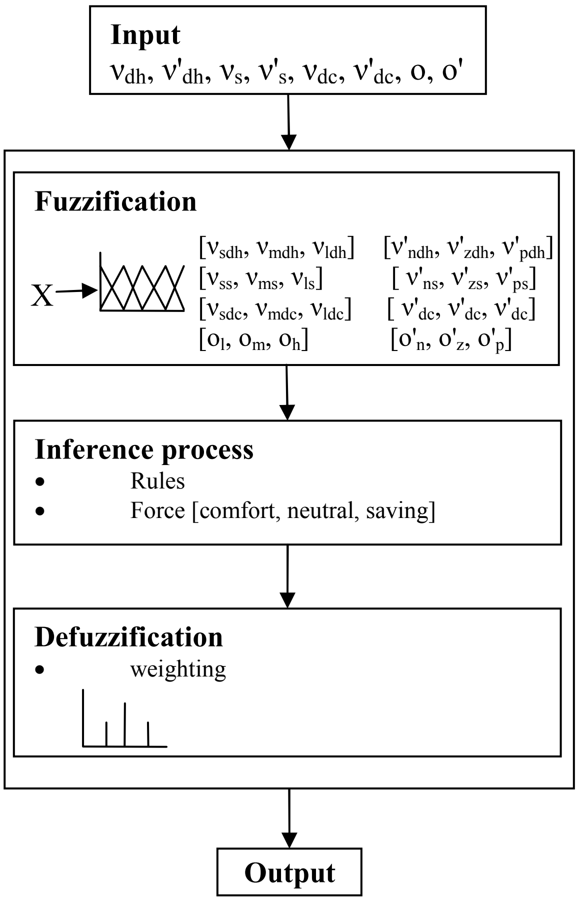

Fig. 2 Fuzzy logic model.

5 Method

Through sensors and thanks to the current 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 objective of the model is to provide a reliable system with an easy implementation, hence the simplicity of the inputs required.

5.1 Parameter of design

t: Time period after which an analysis is computed and a subsequent decision is made with regard to the climate setting type.

5.2 Initial variables of the model

Ashrae (1997) [27] defines a range of assessments that could give a user: hot, warm, slightly warm, neutral, slightly cool, cool and cold temperature. This range of values is extensive; some components take the same value as regards to the pattern that is wanted to search. Thus, we reduce this range to three components: Dissatisfied by heat, satisfied and dissatisfied by cold. The following variables are defined:

- ν_{dh}, ν_s, ν_{dc}: Total valuation during t-period of the users. The evaluation may be: Dissatisfied by heat, satisfied and dissatisfied by cold.
- ν'_{dh}, ν'_s, ν'_{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 variations of the total valuations during two consecutive different periods are calculated as follows:

$$\nu_\alpha'\big|_{\Delta t} = \frac{\nu_\alpha\big|_{\Delta t} - \nu_\alpha\big|_{\Delta t-1}}{\nu_\alpha\big|_{\Delta t-1}} \; with \; \forall \alpha \in \{dh, s, dc\} \tag{1}$$

$$o'\big|_{\Delta t} = \frac{o\big|_{\Delta t} - o\big|_{\Delta t-1}}{o\big|_{\Delta t-1}} \tag{2}$$

5.3 Conversion of the variables to fuzzy variables (fuzzification)

Depending on the relative position of the previously defined variables regarding to valuation expected during the interval, each variable is divided, in percentage terms, 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:

- ν_s, ν_m, ν_l: Component of set small, medium and large of the users, respectively.

As far as to variation is concerned, as much in negative sense as positive, the number of users who value between two consecutive periods, also is divided into three parts or component percentages depending on the sign of the variation between periods:

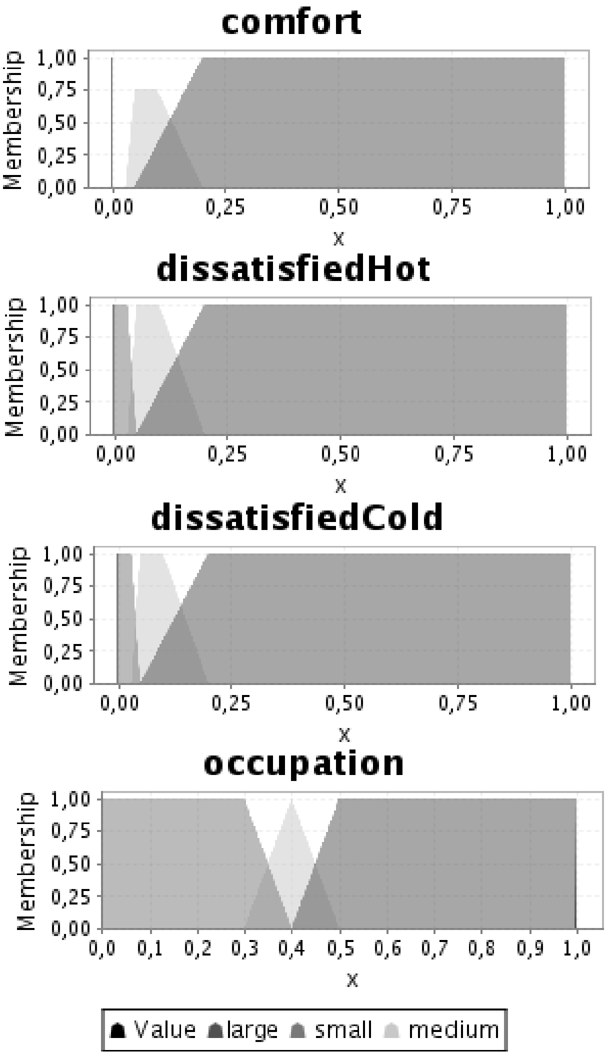

Fig. 3 Membership functions of comfort and its variation.

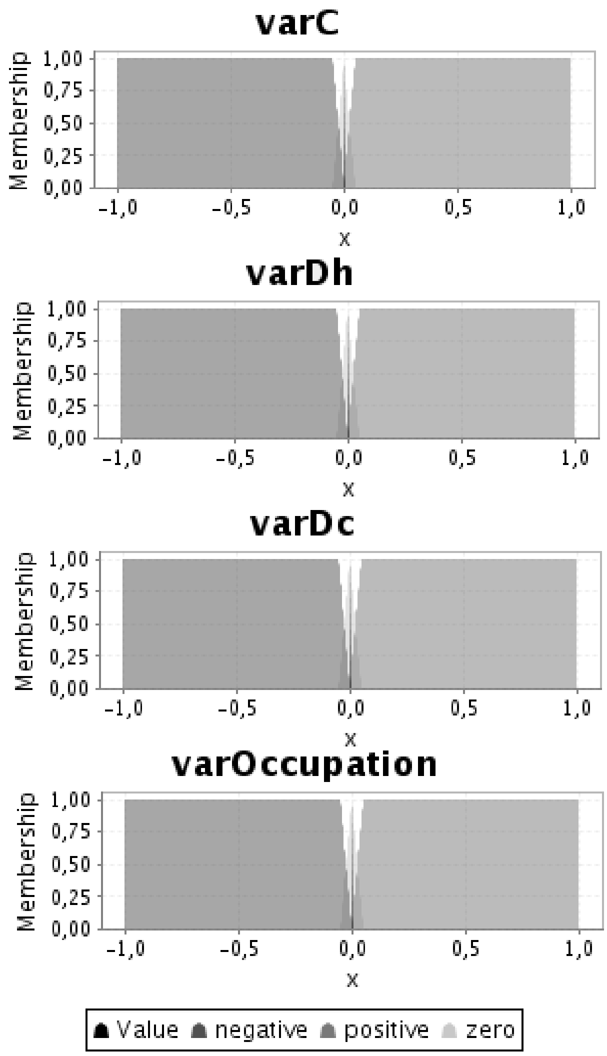

Fig. 4 Membership functions of dissatisfied by cold and its variation.

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

The variables are represented by the exact quantification of their component, and are shown in the figures 3 and 4.

In figure 3, we present the membership function, with its variation shown in figure 4. In the membership function of comfort, the membership consideration to the small group has been underestimated and in medium group has been devaluated. The reason of this change is that the users are not forced to indicate that are in a comfortable situation whereas use the system when they are dissatisfied. It can be observed that if these changes would not have been considered the system would give the same value to the dissatisfied people that to the satisfied people that have decided to respond.

Moreover, the total occupation of users during the t-period is represented by three components that define it in terms of total quantity:

– o_l, o_m, o_h: Component of low, medium and high occupancy, respectively.

With respect to the variation (upward or downward) between two consecutive periods, each parameter is also divided into three parts or component percentages depending on the sign of the change between periods:

– o'_n, o'_z, o'_p: Variation of negative, zero and positive occupation, respectively.

The variables are represented by the exact quantification of their component (see figure 3-4).

5.4 Inference process based on fuzzy logic

Once the three components of each variable are obtained, a set of logical rules is calculated considering the variation from the previous period:

$$R1: \; v_{hdh} \;\; \&\& \;\; v'_{pdh} \;\; \&\& \;\; o_h \;\; \&\& \;\; o'_p \;\; then \;\; Out = comfort$$
$$R2: \; \ldots$$
$$\ldots$$

The rule R1 indicates the preference that should be given to the comfort if the occupation of the building is high, its variation is positive (the users are coming), the number of users dissatisfied by heat is increasing and its variation is also positive. In this rule, the logical && represents the lowest among the four factors. The meaning of comfort, neutral and savings are used to show that a significant change in global level exists of comfort 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 saving components are calculated by applying of the root of the quadratic sum of all the rules associated to each of them:

$$force_{\alpha} = \sqrt{\sum_i R_i^2} \quad \forall R_i \in \alpha \; with \qquad (3)$$
$$\forall \alpha \in \{comfort, neutral, saving\}$$

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

To make a decision about which demand that must prevail (the user comfort or saving into a central system), it is necessary to transform the previous results of the inference process into a single interpretable result mathematically in the form of probability. A representative example of each of the forces is presented in figure 5. This is the result after growing a positive variation for the occupation to 31%, while the evaluation for comfort and 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.

Where 0'3, 0'5 and 0'7 represents, respectively, the "centers" membership functions of Comfort (c), Neutral (n) and Saving (s) that are showed in figure 6.

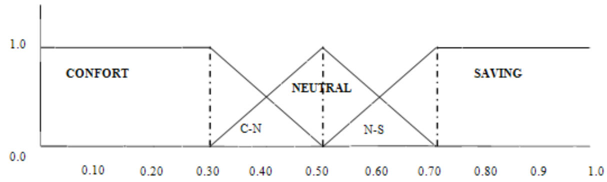

Fig. 6 Membership Functions.

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

$$weighting = \left(\begin{array}{l} [C.center]\cdot[C.force]+ \\ [N.center]\cdot[N.force]+ \\ [S.center]\cdot[S.force] \end{array} \right) \Big/ \begin{array}{l} [C.force]+ \\ [N.force]+ \\ [S.force] \end{array} \qquad (4)$$

Figure 7 shows the value solution of the output membership function for the case shown in figure 5. The center of gravity, associated to the behaviors that are defined, is obtained. In other words, the reference point is shown with respect to the centers that represent the *Comfort*, *Neutral* or *Saving*. On this point, the behavior pattern in the analyzed period is deduced. Furthermore, as not only the flow size is considered but also this variation in a period before, through the careful preparation of the rules, not only the pattern of comfort can be detected, but also the error in next period can be predicted with a very small probability. All this, using a little amount of possible information and due to temperature or

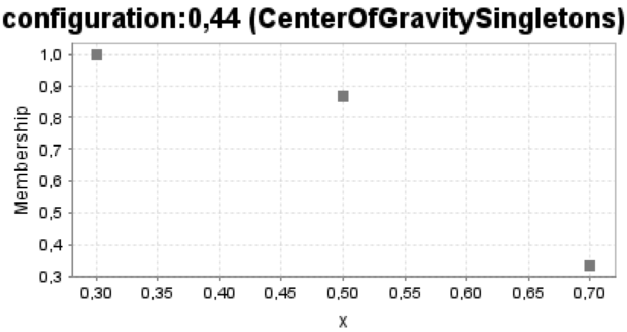

Fig. 5 Centers force.

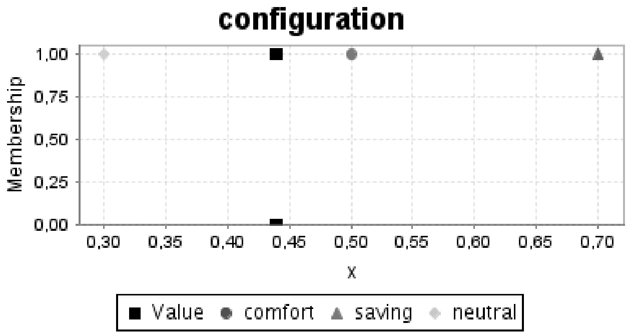

Fig. 7 Outputs.

the particularities of each user are not known. The decision logics rules, in case that several types would be detected, the answer would be given with greater probability value.

6 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 78.37m^2. 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 8 and 9.

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.

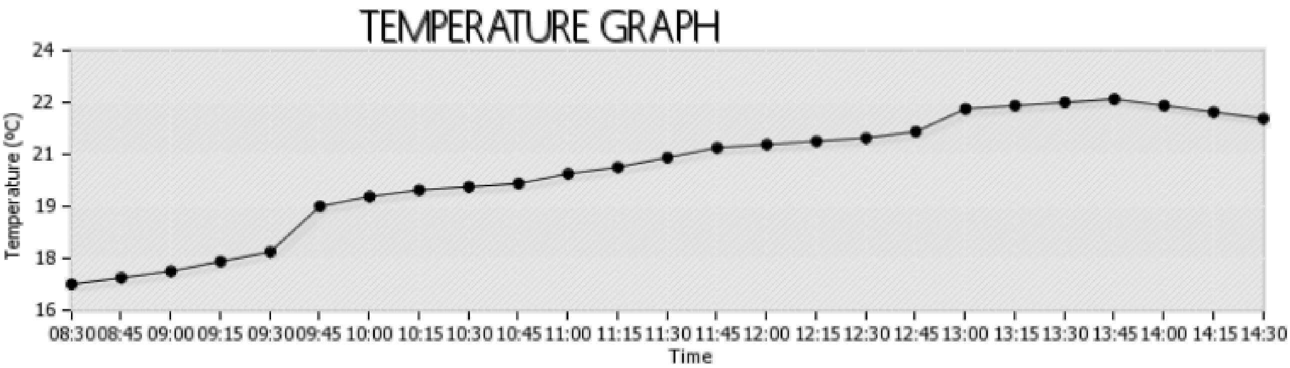

Fig. 8 Temperature of room A.

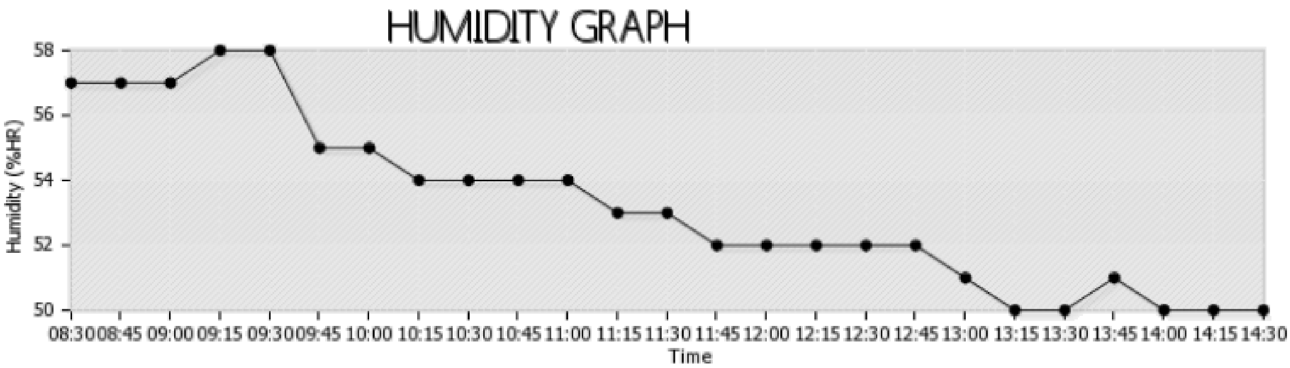

Fig. 9 Humidity of room A.

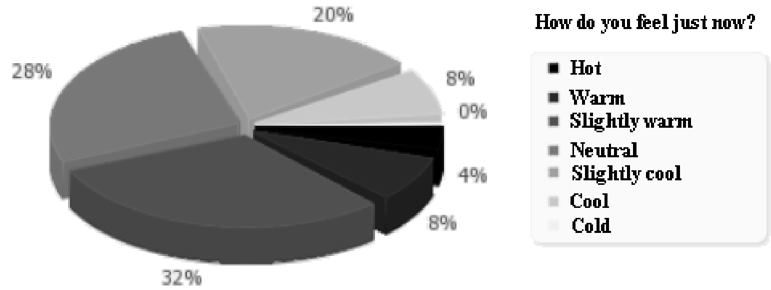

Fig. 10 User's answers.

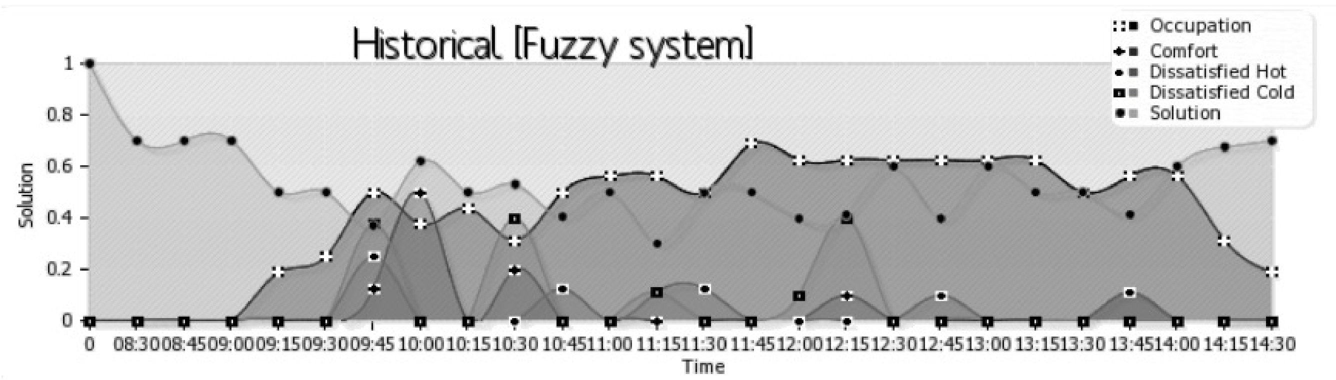

Fig. 11 Chronological results of the fuzzy-logic system.

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.

Finally, we calculate an approximation of the PMV and PPD indices [28, 29] (Figure 12, 13), applying the following values:

– Air Temperature (ºC): Is the average of the two temperature sensors measured every 15 min.

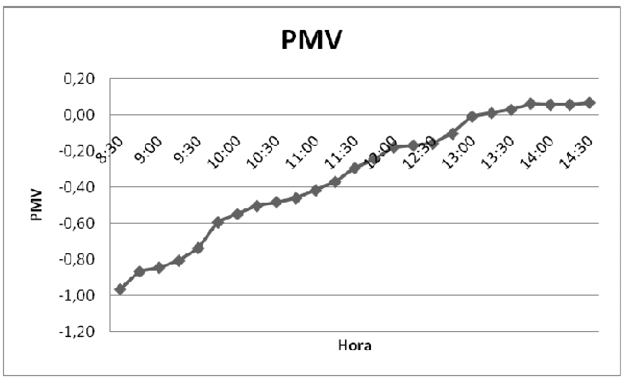

Fig. 12 Predicted Mean Vote Index.

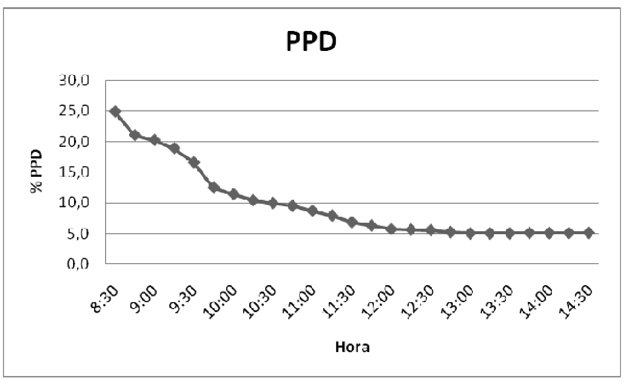

Fig. 13 Predicted Percentage Dissatisfied Index.

- Mean radiant temperature (ºC): Is the average of the two temperature sensors measured every 15 min.

- Relative air velocity (m/s): 0.1m/s

- Relative humidity (%): Is the average of the two humidity sensors measured every 15 min.

- Clothing (clo): We have applied 1 clo, due to the type of clothing described and the rules applied in AENOR [30].

- Metabolic rate (met): We have applied 1.2 met, which corresponds to the type of sedentary activity which normally takes place in offices and in front of computers. The selected value is indicated in the AENOR standard [30].

The comparison of results between the survey output and the PPD index highlighted that the percentage of dissatisfied users according to the PPD index is smaller than shown by the survey. This shows that the survey detected discomfort levels at specific times of the day that were not reflected in the PPD index, which proves that our system can improve the comfort and savings more accurately than systems that apply the PPD.

7 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.

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