



Control of HVAC system comfort by sampling

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Abstract

The sampling of the users comfort, allows observing and predicting the level of comfort on the HVAC (heating, ventilation, and air conditioning) systems. The development of online sampling systems assists in the recognition of the behavior patterns that occur in the offices.

This paper presents a user-friendly tool designed and developed in order to make easier knowledge extraction and representation to make possible decisions about which demand that must prevail, the user comfort or saving into a central system. This decision may depend on the occupation and feeling of comfort of its occupants.

Some studies have put neutral thermal conditions outside the ranges of comfort of the ASHRAE standard. The actual rules of the HVAC systems are based on studies carried out on specific populations in a specific space, which are not valid in certain situations. This is a dynamic idea of the comfort based in real data.

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. 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, thanks to a questionnaire of imprecise answers. We seek an improvement in the building users, regardless of their particularities.

Keywords: comfort, expert system, HVAC, fuzzy logic, sampling.

1 Introduction

Many human comfort models were developed in the last years attempt to predict a better approximation to reality, such as a human feels in a given environment. In general, the patterns of thermal comfort models are based on studies carried out on specific populations in a specific space, which are often analysed using models that follow the idea that these can be used in all building types in the same manner. 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) (Soyguder, 2009). Table 1 shows some 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 (Van Hoof, 2008), although it is not fully applicable to all parts of the globe, PMV models approaches us the reality, but can be improved with one design for each building.

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 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.

Table 1: Several studies in the past

Authors	Methods & variables														
	PMV	PID	Fuzzy Logic	Neural Networks	Genetic Algorithm	Agents and MAS	Learning	Fixed or reactive preferences	Survey preferences	Temperature	Humidity	Ventilating	CO ₂ Quality	Lighting	Energy Consumption
Argiriou et al., 2000	x	x	-	x	-	-	x	x	-	x	x	x	x	-	x
Argiriou et al., 2004	x	x	-	x	-	-	x	-	-	x	x	x	x	-	x
Calvino et al., 2004	x	x	x	-	-	-	-	-	-	x	x	-	-	-	x
Dalamagkidis et al., 2007	x	x	x	-	-	-	x	x	-	x	x	x	x	x	-
Davidsson y Boman, 2005	-	-	-	-	-	x	-	x	-	x	x	-	-	x	x
Doctor et al., 2005	x	-	x	-	-	-	x	x	-	x	x	x	x	-	x
Dounis y Manolakis, 2001	x	-	x	-	-	-	-	-	-	x	x	x	-	-	x
Dounis y Caraiscos, 2008	x	-	x	-	-	x	x	x	-	x	x	x	x	x	x
Duangsuwan y Liu, 2009	-	-	-	-	-	x	x	x	-	x	x	-	-	x	x
Gouda et al., 2006	-	x	x	x	-	-	x	x	-	x	x	-	-	x	-
Guillemin et al., 2002	x	-	x	-	-	-	x	x	-	-	-	x	x	x	x
Hagras et al., 2003	-	-	x	-	x	x	x	x	-	x	-	x	-	x	-
Hagras et al., 2004	x	-	x	-	x	x	x	x	-	x	x	x	x	x	x
Hamdi y Lachiever, 1998	x	-	x	-	-	-	-	x	x	x	x	-	x	x	x
Huang y Lan, 1997	-	x	-	-	x	-	-	x	-	x	-	-	-	-	-
Kolokotsa et al., 2001	x	x	x	-	-	-	x	-	-	x	x	x	x	x	x
Kolokotsa et al., 2002	x	x	x	-	-	-	-	x	-	x	x	x	x	x	x
Kolokotsa, 2003	x	x	x	-	-	-	-	-	-	x	x	x	x	x	x
Liang y Du, 2005	x	-	x	x	-	-	x	-	-	x	x	x	x	-	x
Liang y Du, 2008	x	-	x	x	-	-	x	x	-	x	x	x	-	-	x
Magnier y Haghghat, 2010	x	-	-	x	x	-	x	-	-	x	x	x	-	-	x
McCartney y Nicol, 2002	-	-	-	-	-	-	x	-	x	-	x	x	x	x	-
Mo y Mahdani, 2003	x	-	-	-	-	x	x	x	-	x	x	x	x	x	x
Moon y Kim, 2010	x	-	-	x	-	-	x	x	-	x	x	x	-	-	x
Morel et al., 2001	x	-	x	-	-	-	x	-	-	-	-	-	-	-	x
Nicol y Humphreys, 2010	-	-	-	-	-	-	x	-	x	x	x	x	-	-	-
Qiao et al., 2006	x	-	-	-	-	x	x	x	-	x	x	x	x	x	x
Rutishauser et al., 2005	x	-	x	-	-	x	x	x	-	x	x	x	x	x	x
Shahnawaz Ahmed et al., 2007	-	-	x	-	-	-	-	-	-	x	x	x	-	-	x
Shepherd y Batty, 2003	-	-	x	-	-	-	-	-	-	x	x	-	-	x	-
Soyguder y Alli, 2009	-	x	x	x	-	-	x	-	-	x	x	-	-	-	-
Soyguder y Alli, 2010	-	x	x	-	-	-	-	-	-	x	x	x	-	-	-
Tripolitakis et al., 2004	x	x	x	-	-	-	-	-	-	x	x	x	x	x	x
Wang et al., 2000	-	-	-	-	x	-	-	x	-	x	x	x	x	-	x
Wang et al., 2002	x	-	-	-	-	-	-	x	-	x	x	x	x	x	x
Wang et al., 2004	x	-	-	-	-	-	-	x	-	x	x	x	x	-	x
Wright et al., 2002	x	-	-	-	x	-	x	x	-	x	x	x	-	-	x
Yalcitas y Akkurt, 2005	-	-	-	x	-	-	x	x	-	x	x	-	-	-	x

Due to differing perceptions of what is 'comfortable', that occur because some people are more tolerant to broader climatic conditions than others. Obviously, whether the standard is accepted or not clearly depends on the place's weather and the building's conditions. Therefore, without questioning the standard, comfort systems whose ventilation and air-conditioning is based on personalised comfort models must be developed.

The energy saving should not take precedence over comfort, especially 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 (Almirall, 1995), after breakfast and meals, etc. These all have an effect on human's thermal sensation and usually occur in conjunction with one another.

There are different examples both in printed or internet-based studies, where the sampling was based on surveys using sampling methods. The aim of these surveys was to obtain the staff's general level of comfort at the start or end of the day. 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 (Huizenga, 2002; Young, 2011). But as Brager says "An important premise of the adaptive model is that the person is no longer a passive recipient of the given thermal environment, but instead is an active agent interacting with the person--environment system via multiple feedback loops." (Brager, 1998). As seen in (Aparicio, 2011), a previous experimentation has developed through a system based on a fuzzy logic system.

2 Online comfort survey

It has been proved that there is often an acute discrepancy between the objective and subjective comfort (Meir et al., 2009). In contrast to the objective of comfort presented by ASHRAE thermal comfort in this study is used the survey as a fundamental element of subjective data collection.

The survey allows knowing the different perceptions of the users about indoors comfort levels. The system stores information relating to the comfort related to the temperature and humidity at the moment when the survey data are collected. We used the international standard ISO 10551:1995 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 2. The users filled in 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 2: 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.

3 The designs based on fuzzy logic

The reasoning of fuzzy logic (FL) are very simple and flexible, the "naturalness" of its approach and not its far-reaching complexity. FL is suitable with imprecise data as comfort, this is used in everyday language, but the same vocabulary to different people may have different values, these values are known thanks to a questionnaire of imprecise answers, in this case the fuzzy logic is the easiest methods to use. In direct contrast to neural networks, which take training data and generate opaque, impenetrable models, fuzzy logic allows to ensure the reaction of the system on based to the experience of people who already understand and know the system.

The main objective of the design is to provide an online reliable pattern detection system but at the same time, an easy implementation. The situational patterns search permit to obtain useful information in takes decision; this suggests the use of the artificial intelligence techniques. The fuzzy logic 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 1): 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 expressed or are proposed out through the experience of the expert.

Nowadays, there is a standard for implementing fuzzy logic, especially for fuzzy control, called Fuzzy Control Language (FLC) that facilitates the development with APIs which allow implementation in different languages (IEC, 1997).

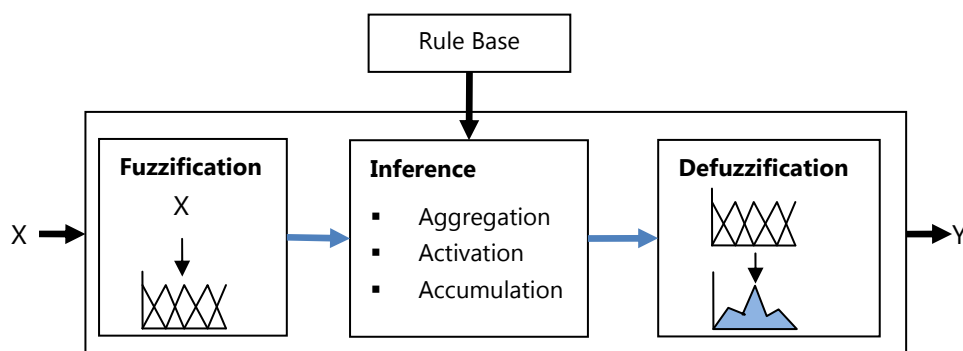


Figure 1: Basic configuration of a fuzzy logic system.

Through sensors and thanks to the current technological tools with Internet access, the users could be assessed and their comfort could be personalized, in all situations and wherever. In addition, they can register the measure 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 (variables):

percentage and variation of occupancy, the evaluation may be dissatisfied by heat, satisfied and dissatisfied by cold. First, the fuzzy logic system converted the variables to fuzzy variables (fuzzification). Once the components of each variable are obtained, a set of logical rules is calculated considering the variation from the previous period (inference process). An example of rule is, "The preference that should be given to the saving energy if the occupation of the building is low, its variation is negative (the users are leaving the rooms), the number of users dissatisfied by heat is decreasing and its variation is also negative". The answers of the fuzzy rules (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. Finally, 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 (defuzzification).

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 independently of temperature or the particularities of each user. The decision logics rules, in case that several types would be detected, the answer would be given with greater probability value. This analysis is always made after a specific time period and a subsequent decision is made with regard to the climate setting type.

4 Experiment and results of fuzzy logic system

The model has been validated in one real case scenario in two work spaces of the Higher Technical School of Engineering of the University of Seville. 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 9-13°C and over 80% humidity. The temperature and relative humidity inside the work area was measured during the study. In (Aparicio, 2011) could be seen an example of survey result as comfort condition, personal and thermal condition or the emotional condition.

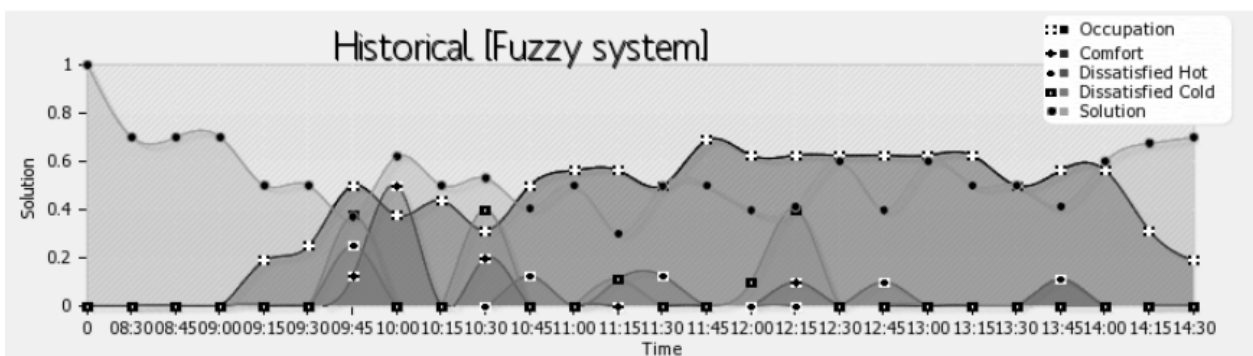


Figure 2: Chronological results of the fuzzy-logic system (Aparicio, 2011).

The answers to each question as well as the level of occupation are shown in Figure 2. The solution's weighting is shown where a one represents maximise saving and a zero maximise comfort. Furthermore, this figure presents the results of occupation and the answers of comfort, dissatisfied by hot and by cold.

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 leans more towards comfort due to the high occupation of the space, which was modified according to the users' answers to the questionnaire.

The trend in the system, allows you to be away from specific situations, due to psychological factors, health (body temperature), the menstrual cycle in women (Figure 3b), etc. For these reasons, some people may require a specific temperature due to the difference in the corporal temperature as you can see in (Figure 3a). However, in the building the user should adapt to the group. The needs of comfort are related to the body thermal curve, and at the beginning in the morning, the results in (Figure 2) is shown needs of comfort which are reduced in the same way as body temperature increases.

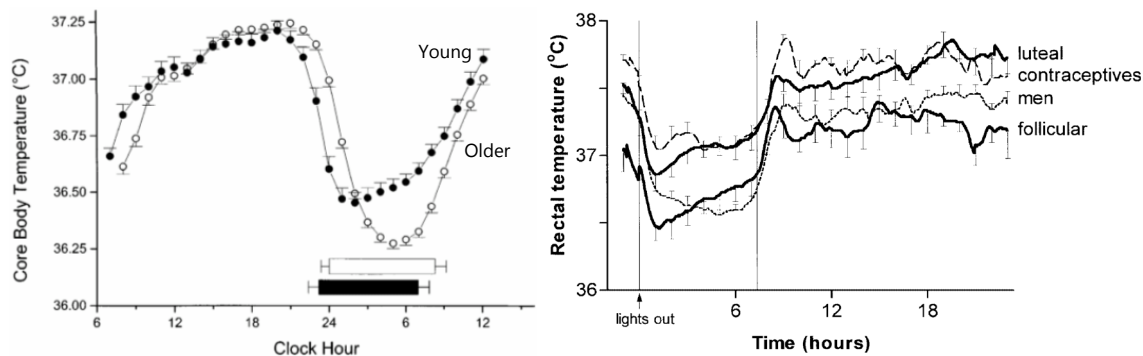


Figure 3: (a) The figure at left shows the core body temperature waveforms averaged with respect to time of day for young and older subjects. Source: Duffy, 1998. (b) The figure at right shows the rectal temperatures in men, women taking hormonal contraceptives, and women in the phases of their menstrual cycles. Source: Backer, 2001.

5 The system architecture

The structure of the system is being investigated, as shown in the Figure 4, it is based on the user's response to the surveys, rather than being controlled by a remote control to select the setpoint of the temperature. This allows to control the humidity, which generally could not be chosen by users.

The survey information together with the data of temperature, humidity and occupation given by the sensors are stored in a database. The fuzzy logic system gets the information to examines the criteria for selecting the proper temperature and humidity.

In a second phase of the system, taking into account the outcome of the fuzzy logic system, and information stored in the comfort of each individual, together with the data or cost function of the change of condition, the change value is the value at which the change in the measurement result is considered desirable due to the comfort and saving criterias. This second system takes the decision on the HVAC, it must be preserved and implemented in the following periods of time.

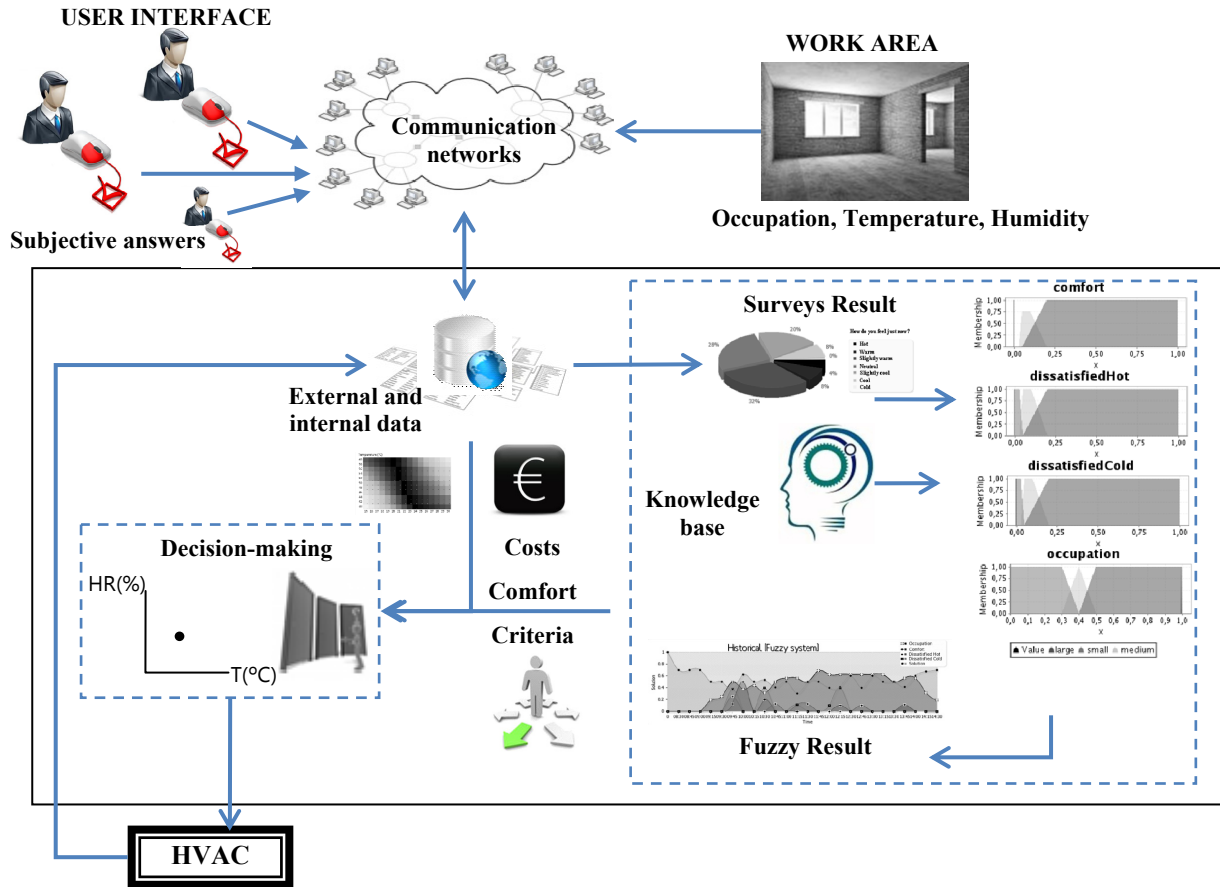


Figure 4: The system architecture

Individual user values are grouped in the system, generating rates of states of comfort regarding different climatic conditions of the rooms (after training the system). In Figure 4, based on these values, it is known the difference of comfort regarding the current room status. Furthermore, if it is known the consumption differential for a temperature change in a room. The most interested change is selected with respect to the criterion given by the fuzzy logic system.

The survey responses are stored individually for each user, the system learns the individual results, and these can be compacted into a general model or for each room.

It is stored for each interval of temperature and humidity, the average acceptance by the user group. After the first day, we find temperature and humidity ranges for which we would not know any data, in (Figure 5) is represented by crosses.

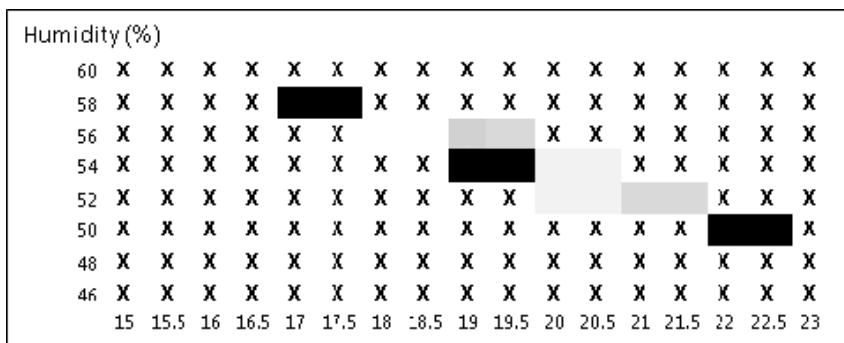


Figure 5: First Day

But over time, we will find similar comfort models which will follow the Fanger comfort curve (Figure 6a), but certainly more real to user comfort (Figure 6b).

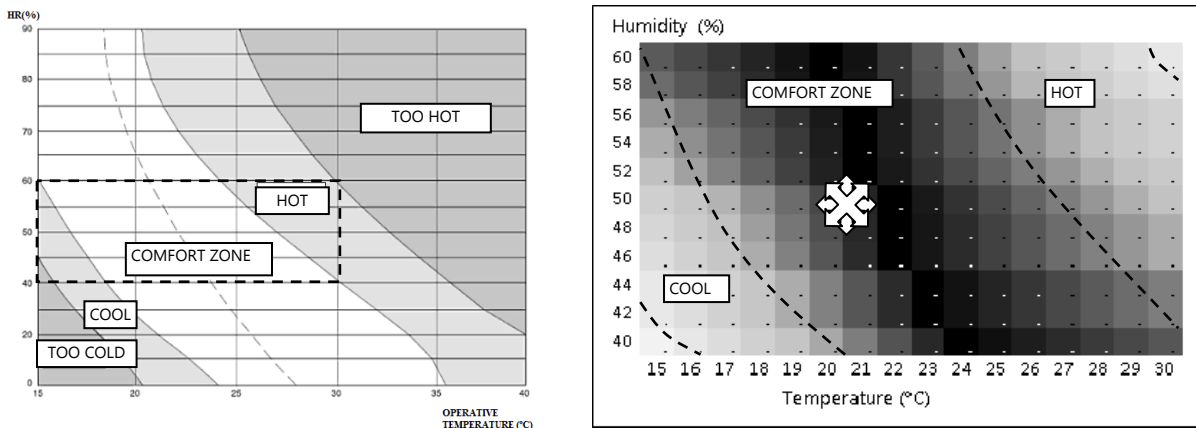


Figure 6: (a) The figure at left shows the comfort curve of Fanger. Source: Mondelo, 1995. (b) The figure at right shows a possible degree of comfort in a building.

As shown in Figure 6b, assuming that we are at a point (22°C, 50% RH) only has to calculate the differential of comfort with respect to the closest points. The amount of energy that must be applied, must be lower due to evaporative systems, those systems can significantly reduce the energy consumed to a change in the degree of comfort. This kind of systems has shown around 15% savings in annual energy consumption of the building, while maintaining the comfort most of the hours in the year. (Khandelwal, 2011).

The architecture of this system aims to bring new decisions to be taken on such systems, where users are aware of the humidity, but they will not be able to control their changes.

6 Conclusion

There is a need to assure that the saving energy perspective is explicitly present, without prejudice to the comfort in the building. Nowadays, these two perspectives are not connected; this research is a chance to balance the scales a little. The HVAC systems efficiency and flexibility need to be balanced with considerations of users. A new HVAC control strategy and decision criteria that regulates thermal comfort levels was presented. Fuzzy logic is applied to the user's evaluation and the actual status. To obtain a criteria that is the way in which is decided to change the system in order to create indoor thermal comfort and saving energy.

The system will dynamically adapt to changes in comfort, will store the user responses dynamically to meet your individual comfort. This allows knowing the effect of changes in the decisions of the system.

Logically, we are developing a technique in order to prevent the problems and infighting for the selection of temperature within a workspace, where the air conditioning is not to everyone's taste.

The architecture of the proposed control system allows easier evaluation of the indoor climate by using surveys. It is expected that the outcome of this project will show that the control based on thermal comfort surveys provides better comfort at a lower cost than that provided by thermostatic control techniques.

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