Evaluation of comfort conditions in architectural design assisted by fuzzy logic

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***Abstract*— We present a fuzzy inference system (FIS) that assists in the evaluation of comfort levels in buildings. From a suggested sustainability design model, based in LEED^{TM}'s considerations and recommendations, comfort is analyzed from six different perspectives: temperature, humidity, lighting, acoustic (noise), air (ventilation) and visual relief. These variables are measured through well known units, with convenient definitions established, and fuzzified in order to relate them through inference rules to achieve a qualification of the comfort level based on architectonic criteria. Real data from indoors of mexican buildings allowed to evaluate the model's performance. The result is an expert system capable of ranking either existing or in development buildings.**

Keywords: Comfort, fuzzy inference system, architectonic design

I. Introduction

Sustainability can be defined as the ability to meet current needs without compromising those of third and future parties (Herman, 2002; Natural Resources Institute, 1992). Although it is a concept whose need is becoming increasingly more proven, its assessment has many features of subjectivity, a human concept. In this sense, fuzzy logic (Zadeh, 1965) is able to emulate the subjectivity of human thought through establishing a generalization on the membership degree of the elements of a set and on the level of truth of inference-type logical propositions.

In general, attempts to evaluate the degree of sustainability achieved by a project or structure are related to the knowledge that an expert may have on the subject. In order to simulate human reasoning, fuzzy logic also needs the synthesized knowledge of the variables that can be observed on the field of interest, and produce thereby an emulation of the qualification that an expert could give through a process of thought (Zimmerman, 1991).

With reference to sustainability, the design and construction of buildings require the use of various methodologies and models to make them sustainable, i.e. to include criteria for sustainability throughout the entire life-cycle of the building (Hernández-Moreno, 2010). One of these methodologies is known as Leadership in Energy and Environmental Design (LEED^{TM}), a method used not only to reduce the environmental impacts caused by the buildings but also to improve and assess the conditions of welfare and functionality of the building (United States Building Council, 2009). It may both save resources of all kinds and improve the quality of life of users and the environment. Basically, this methodology considers six strategies: site, water, energy, indoors comfort, construction materials and scrap management.

These ideas are not new (Marsh and Raines, 2009). The modern beginnings on serious works to improve the conditions of life of buildings began around 1993 (CSA, 2001). For example, the international standards organization (ISO) has developed the standard ISO/TC59/SC14 concerning ”life design” to assist in the design of buildings and to improve their conditions of use and performance (Performance Based Building Thematic Network, 2005). However, there is little work where sustainable design and fuzzy logic have been combined. Apart from Roscia (2008), an exhaustive search does not cast more results in this regard.

The present paper deals with two main focus to these issues. On one hand, it raises criteria relating to sustainable design for Mexican buildings. Even though we have other methodologies as inspiration (BREEAM, CASBEE, Green Star, DGNB (Delgado-Hernández *et al.*, 2010)), the authors have studied the advantages that could be brought to the Mexican case. Furthermore, as it will be seen later, LEED^{TM} strategies can be translated into sets of measurable variables. In this document we show those related with the indoor's comfort strategy through variables that try to give a quantitative sense, also serving as inputs to the fuzzy inference system presented herein.

Moreover, the system of fuzzy inferences is designed in such a way that any professional with knowledge concerning the measurement of variables such as temperature, humidity, lighting, acoustic noise, air renovation and visual relief, could use it as an assistant in the determination of a level of sustainable comfort for the direct and indirect users of a hypothetical or real building, either at its design or operation stage. This type of assistance systems, also called expert systems (Yen *et al.*, 1995), does not try to replace human beings in activities in which their criterion is required, but are useful in preliminary or partial studies concerning procedures related to diagnosis or rating (Rosas-Jaimes *et al.*, 2005; Rosas-Jaimes *et al.*, 2006).

In the next section, the proposed criteria to implement a methodology of sustainable indoors' comfort of a building, specially for Mexican conditions, is presented. The mexican case has been selected because of the variety of weather conditions that exists throughout the country, ranging from northern deserts to southern jungles. Note, however, that only cases in the central region of the territory have been considered in this stage of the research, where weather conditions do not vary significantly over the year. Section III, describes the variables, rules and global structure of the fuzzy inference system that serves as a tool in the qualification of the degree of sustainability that a building could reach given specific criteria. Section IV shows the results of a study of real cases, comparing the outcomes with the opinion of human experts for the same cases. Finally, the future activities and conclusions for this work are discussed.

II. Sustainability methodology criteria for comfort

LEED^{TM} strategy for indoors' comfort is a list of criteria difficult to measure, and rather they rely on the appreciation that an inspector could have. For example, it is possible to see among those criteria some like "tobacco control" or "clean and healthy inner environment supply". It is clear that it is very difficult to obtain some measured quantity to this concepts. On the other hand, even though concepts like "good thermic conditions" or "good luminous conditions" are also vague, it is possible to relate them through variables capable of measurement, like temperature or lighting intensity. In an effort to quantify these approaches to a more objective set of values, we propose six variables that match as much as possible with the indoors' comfort concept established in the LEED^{TM} methodology.

A. Temperature

This variable is associated with that of the human being in our context. A room temperature must motivate a sense of comfortability if the heat transfer between the environment and the subjects is not a cause of heatedness or cooling. It is measured in a convenient scale, like Celsius degrees. We have taken a 0–50 degree scale and denote this value by T_C, being an interval of 20–23°C considered as ideal (ISO, 2003; ISO, 2008).

B. Humidity

Humidity is expressed as a percentage of the concentration of water vapor in a volume of air. We use the relative quantity of this variable. This variable is important because of its relation to the capacity of the human body to refresh itself, which is directly associated with a sensation of comfort, it depends on the quantity of water vapor in the environment. A 0–100$\%$ of humidity scale, denoted by H_C, has been defined for our work. A 40–60$\%$ of indoors' humidity is recommended as ideal (ISO, 2003).

C. Acoustic Volume

It assesses the exposition levels of the building users to the environmental noise. It is generally measured in decibels (dB). The scale for acoustic volume A_C goes from 0 dB to 110 dB, but the recommended range is 35–48 decibels (ISO, 2004).

D. Lighting

It is the incident and environmental light energy in human eyes. We measure lighting L_C in $luxes$ ($lumen/m^2$). We have taken a 0–2000 luxes scale for our fuzzy variable. It is considered that a range of luminous comfort varies according to the building and the activities in it. In offices, for example, a 400 – 700 luxes range is considered adequate (ASHRAE, 2004).

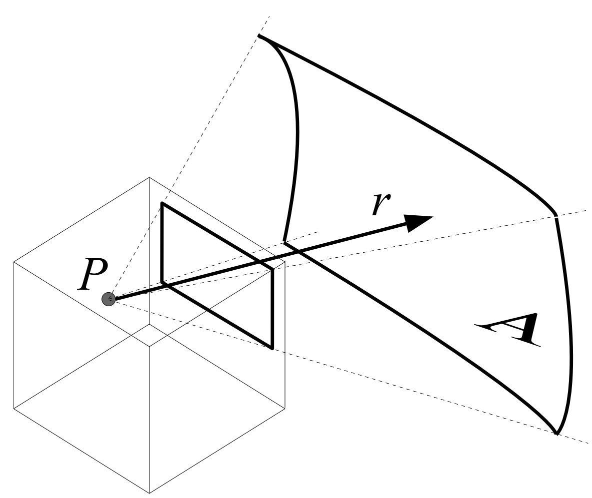

Figure 1. Steradian definition

E. Visual Relief

This variable is concerned more with human psychology through the sensation of relief provided by the capability of seeing outdoors through windows. We propose to measure this variable through an adequation of the definition of steradian

$$\theta = \frac{A}{r^2} \tag{1}$$

Figure 1 depicts an outdoors surface A that is seen by a user through a window from an indoors point of view P, from which a radius r is projected to reach A. Evidently, the extension of surface area A that can be seen by a user in P is affected by the size of the window that separates indoors from outdoors. The same can be said about the relationship of the solid angle θ (not depicted) and the separation of P and this window.

Due to it is easier to get a measure for r (with a measuring tape or a laser rangefinder) and for θ (with proper devices or by means of trigonometry), the resultant area in equation (1) is better written as

$$N_C = r\,\theta \tag{2}$$

In a simple case, this surface is another building wall[1], but in most cases it will be a combination of surfaces located at different distances, so it is considered convenient to take an average of the most significant ones. In this way, a room with no windows have a null visual relief, but one with windows and far objects from it have a high visual relief (r, and hence A, tends to ∞ when the room users can see the horizon). The range for this variable goes from 0 to ∞ m^2 .

We have no reference to consider an ideal range of values for this variable, then we propose here a range from 10 to 100 m^2 as an ideal set of values.

F. Ventilation

Ventilation in buildings is based on the interchange of air volumes from outdoors to indoors, and it is related with the temperature equilibrium and the oxygen rate present in a room. Ventilation V_C is measured in m^3/hr and an ideal range is considered to be 0.25–0.75 m^3/hr (ISO, 2008).

Having presented the six variables under study. Table I summarizes both their ranges and units. Now, the proposed fuzzy system will be presented.

III. Fuzzy Inference System (FIS)

To fuzzify the variables that contribute with measured quantities as the inputs, it is necessary to bound a valid and operational interval, and then to divide those intervals for each (T_C, A_C, H_C, L_C, N_C, V_C) by membership functions (MF) indicated by μ.

[1]We are assuming that the area N_C defined in (2) has an equivalence to that of the original definition of steradian, strictly a spherical section.

TABLE I
VARIABLES AND RANGES OF COMFORT

Name	Range	Units	Variable
Temperature	20 – 23	°C	T_C
Acoustic Volume	35 – 48	dB	A_C
Humidity	40 – 60	%	H_C
Lighting	300 – 1200	lux	L_C
Visual Relief	π – 2π	steradian	N_C
Ventilation	0.25 – 0.75	m^3/hr	V_C

We have defined three MFs for each of the six input variables, all of them defined as trapezoid functions. For temperature T_C we have

$$\mu_{Cold}(T_C) = \begin{cases} 1 & \text{if } T_C < 17 \\ \frac{17-T_C}{20-17} & \text{if } 17 \le T_C \le 20 \\ 0 & \text{if } T_C > 20 \end{cases} \tag{3a}$$

$$\mu_{Ideal}(T_C) = \begin{cases} 0 & \text{if } T_C < 17 \\ \frac{T_C-17}{20-17} & \text{if } 17 \le T_C \le 20 \\ 1 & \text{if } 20 \le T_C \le 23 \\ \frac{26-T_C}{26-23} & \text{if } 23 \le T_C \le 26 \\ 0 & \text{if } T_C > 26 \end{cases} \tag{3b}$$

$$\mu_{Hot}(T_C) = \begin{cases} 0 & \text{if } T_C < 23 \\ \frac{T_C-23}{26-23} & \text{if } 23 \le T_C \le 26 \\ 1 & \text{if } T_C > 26 \end{cases} \tag{3c}$$

For $0°C \le T_C \le 50°C$

Figure 2 shows how the temperature T_C is defined under this concept. It can be noted that the function with the lowest values corresponds with the Cold set of temperatures, whereas the highest values correspond with the Hot set of them. Both are ranges that can be considered uncomfortable, in contrast with the central MF that relates with Ideal values of comfort for this variable.

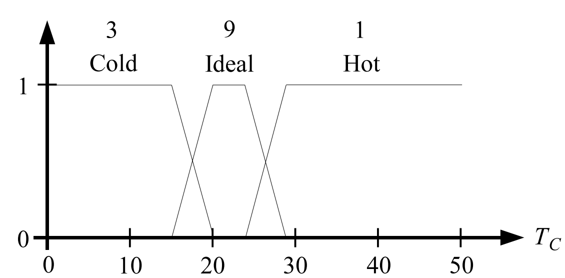

Figure 2. Membership functions of Temperature

It is possible to watch integer numbers associated to each MF (3, 9 and 1 respectively for Cold, Ideal and Hot). These values have the function to avoid ties, when the inference process leads to the combination of

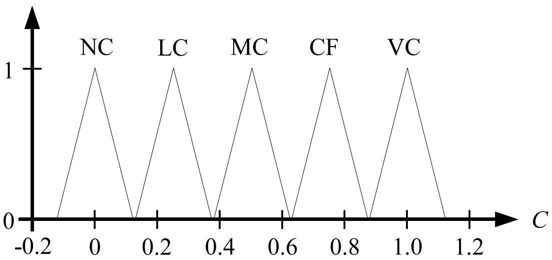

Figure 3. Membership functions of Comfort

rules that results in equal qualification for both extreme membership functions and those of the ideal ones. This scale has been used in the quality management arena (Cohen, 1995). Note that 9 stands for high weights, 3 for moderate and 1 for low ones.

The consequent value (the result for our FIS) will be the variable Comfort C. This variable is fuzzified as can be seen in Figure 3 with five MF: Non Comfortable NC, Little Comfortable LC, Moderately Comfortable MC, Comfortable CF and Very Comfortable VC. These five MFs ensure a finer division on this variable.

Inference rules are used to relate the antecedent and the consequent part, all of them having a form like in expression (4), which result is calculated with mathematical logic

$$\begin{aligned} &\text{if } T_C \text{ is } Cold \text{ and } A_C \text{ is } Noisy \text{ and} \\ &H_C \text{ is } Ideal \text{ and } L_C \text{ is } Dark \text{ and} \\ &N_C \text{ is } Ideal \text{ and } V_C \text{ is } Windy\ THEN \\ &C \text{ is } LC \end{aligned} \tag{4}$$

Our FIS counts $3^6 = 729$ rules. Such a number of inferences are hard to program manually but they can be easily built by means of a combinatory algorithm. This set of inferences gives a direct idea about the process of emulating the way of reasoning of a construction inspector in the qualification of indoors' comfort. The expression that determines the value of such an inference as (4) has the form

$$\begin{aligned} &\mu[(T_C, A_C, H_C, L_C, N_C, V_C),\ C] = \\ &= \min[(\mu_f(T_C) \wedge \mu_g(A_C) \wedge \\ &\wedge \mu_h(H_C) \wedge \mu_i(L_C) \wedge \\ &\wedge \mu_j(N_C) \wedge \mu_k(V_C)),\ \mu_p(C)] \end{aligned} \tag{5}$$

where the symbol $\wedge$ stands for the "AND" operator.

Depending on the values of each one of the antecedent variables, one or several rules will be shot in different levels of membership that will cause the aggregation of portions of area in the consequent part, as seen in Figure 4. It is evident that this Mamdani-type FIS can conveniently be evaluated through the calculus of the centroid abscissa of the aggregated area as

$$\bar{C} = \frac{\int C\, g(C)\, dC}{\int g(C)\, dC} \tag{6}$$

where $g(C)$ is the function plotted by the contour of the aggregated area.

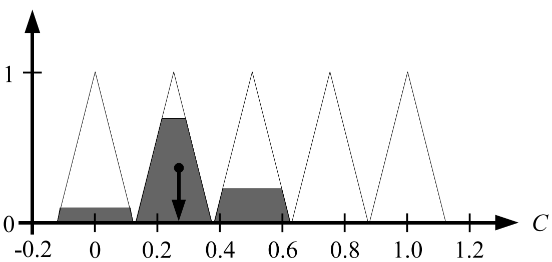

Figure 4. Aggregation of shot rules and defuzzification method

IV. RESULTS

All the presented variables are capable to be measured through metering devices (thermometers, hygrometers, light meters, sound level meters, tape measure, range finders, anemometers) in order to achieve objective values. However, the process for these inputs must try to emulate the human subjectivity, as mentioned.

We use Matlab's Fuzzy Logic Toolbox ® to build and evaluate a comfort level C from this input values by means of our FIS. The software tools permit to focus on the fuzzy logic details, leaving programming of geometry, sets, and calculus in the background. Evaluation of the inputs can be entered by a vectorial presentation, in which the order of the numeric elements must be respected. For our case, we have defined an input arrangement with an order in the variables as presented until now: $[T_C,\ A_C,\ H_C,\ L_C,\ N_C,\ V_C]$.

Table III shows five distinct kinds of rooms for which measures have been taken with proper devices. The obtained values in each case are introduced to our FIS, which estimates the result C, the comfort level for each situation in a scale from 0 (non comfortable) to 10 (very comfortable).

One of the first aspects that can be noticed is the high value for ventilation N_C in the computer server room, in contrast with the other sites. This has a double explanation, which starts with the fact that this is a facility needed for high rates of air exchanges, due to the components homed therein. The other part of this explanation is that we carried on the metering of this variable through an anemometer of middle sensitivity, which required a minimum of air velocity to work.

On the other hand, it is possible to see that some variables vary more than others, but comfort C does not

TABLE II

MEASURED QUANTITIES AND COMFORT LEVELS FOR DIFFERENT ROOM CATHEGORIES

Room	Server room	Library	Gallery	Meeting room	Office
T_C	16.5 °C	22.7 °C	23.1 °C	25.7 °C	25.6 °C
A_C	78 dB	62 dB	62 dB	48 dB	78 dB
H_C	49 %	30 %	30 %	29 %	21 %
L_C	102 lux	314 lux	958 lux	1549 lux	395 lux
N_C	≈ 0	6 m^2	≈ 0	30 m^2	20 m^2
V_C	6600 $\frac{m^3}{hr}$	0.7 $\frac{m^3}{hr}$	0.5 $\frac{m^3}{hr}$	0.3 $\frac{m^3}{hr}$	0.5 $\frac{m^3}{hr}$
C	3.4	7.1	6.6	7.0	5.0

vary in the same proportion. This is due to the quality management scale, presented in Section III, which gives a weight to the MFs for each fuzzified variable, giving priorities in the qualification process.

Furthermore, as can also be seen, four of the rooms are qualified with a good comfortability, except for the office which has a middle value, due to the visual relief measurement. This is interesting, because under a distinct scheme this room could be qualified as comfortable if only the other five variables are taken into account, showing that this psychological term is important.

V. CONCLUSION AND FUTURE WORK

We have shown a Fuzzy Inference System (FIS) that performs an emulation of comfort level qualification. Its inputs are six variables, all of them capable to be measured through metering devices.

Membership functions (MF) have been designed based on requirements established by international community associations, like ISO or ASHRAE, in such a way that our FIS tries to emulate what a human expert could infer with the same values.

We present also a suggested way to define and measure the Visual Relief, a variable that is not defined in precise terms, even though it is widely used in architectonic fields. We think the definitions proposed here could be used to turn it in a more concrete value to adopt.

Our FIS succeed in qualifying distinct rooms like a human expert could. However, further comparisons are needed in order to consider it as a real assistant device for those individuals who work in related fields.

Comfort is only a variable of six factors that LEED™ methodology posses to qualify a broader concept like sustainability. The other five variables (site, water, energy, construction materials and scrap management) can be treated in a similar way, each of them resulting in a level of achievement reached. Furthermore, each one of these results can be used to process them into a bigger FIS in order to obtain a general level of sustainability for a building.

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