A fuzzy logic approach in thermal comfort modelling for naturally ventilated house in tropics

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ABSTRACT

The main objective of this study is to develop a thermal comfort (TC) prediction model suitable for Naturally Ventilated (NV) buildings located in hot and humid tropical climate. More than 1000 data were collected through extensive field survey in Singapore and Indonesia. The survey's finding based on the statistical analyses unveiled that people in the tropics have shown tolerance and different perception of TC than those in the temperate climate. Fuzzy logic concept is adopted to develop an appropriate TC model for tropical NV houses. The complexities of the human cognitive process and the vagueness of linguistic expression are considered in defining their fuzzy membership function. Fuzzy logic rule based model is used to represent human evaluation and perception processes in algorithmic form. A detail exposition of the application which combined the linguistic approach and optimization under multiple thermal condition criteria is presented.

INDEX TERMS

Thermal comfort, Natural ventilation, Fuzzy logic

INTRODUCTION

Human TC is complicated to model mathematically since the real process in human perception (justification over environmental condition) is still unknown and far too complex to understand. Human body is assumed as a "black box" which receives inputs, the environmental and personal parameters, and whose output is the subjective TC perception. The process might be regarded also as a multi-objective optimisation problem on which each of the performance factors are influenced by many parameters. The actual process of human perception is still uncertain and also varied between people even if they are in the same environmental condition. Some uncertainties which have been identified in TC modelling are:

- *Lexical Uncertainty*

  The uncertainty is due to the nature of language used (lexical uncertainty) in describing the environmental parameter. The uncertainty deals with the imprecision that is inherent in most words humans use to evaluate concept and derives conclusions [Kosko 1993].
- *Human Perception Uncertainty*

  This uncertainty deals with the nature of human thermal perception in evaluating thermal condition. In real life, by using abstraction and by thinking analogies, a few sentences can describe complex contents that would be very hard to model with mathematical precision.
- *Subjective Scale uncertainty*

  The other inherent problem is the scale used for TC survey is not always linear quantitative in nature. For example, warm sensation is not perceived as a double of slightly warm or hot is not always double sensation as warm.

METHODOLOGY

The total data of 538 samples from Singapore and 525 data from Indonesia were collected through some extensive field surveys during rainy and dry seasons in the year 2000-2002. In each survey, both objective and subjective measurements were carried out concurrently. The

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purpose of objective measurement is to capture some personal and environmental parameters that are widely used in thermal studies (Clothing, Metabolic rate, Dry Bulb Temp/DBT, Mean Radiant Temp/ MRT, Relative Humidity/RH, and Air Velocity/Vs).

Subjective measurement make a use of ASHRAE scale, and other relevant perception scales (such as airflow, humidity etc). Each question in the questionnaire asks specifically about the present environmental stimulus, and the respondent need to choose only one standardised answer (response) on seven scales voting accordingly.

DATA ANALYSIS

People's TC perception on a particular indoor thermal condition is always differed even though they are exposed to the same environmental condition (room). It is impossible to create a thermally comfortable indoor environment which can satisfy all occupants all the time. Therefore there is no precise description about environmental condition at which everyone perceives it as most comfortable condition. In this perspective, it is understood that TC perception is greatly influenced by environmental conditions (stimuli) but their influences show rather "fuzzy" (imprecise) rather than precise relationship.

The analysis of TC perception only implies the probability of people to perceive and vote according to particular thermal perception scales. One of the powerful statistical methods to analyse TC response is Probit regression analysis. This analysis is drawn originally from studies of threshold pesticide levels and insect kill rates. Probit analysis assumes that the likelihood of an event happening increases as the stimulus intensity increases [Finney 1962].

The probit analysis is applied separately for four environmental stimuli which affect TC perception. The other two personal parameters (clothing, metabolic rate) are analysed separately based on the simple data distribution and mean analyses since the questionnaire do not ask people to vote clothing and metabolic rate. The Probit analysis was applied using SPSS v11 ® statistical software and the results are presented in Figure 1 to 4.

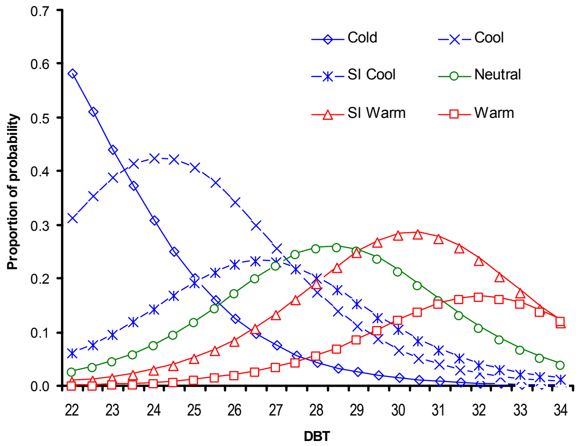

Figure 1: Probit curves for DBT

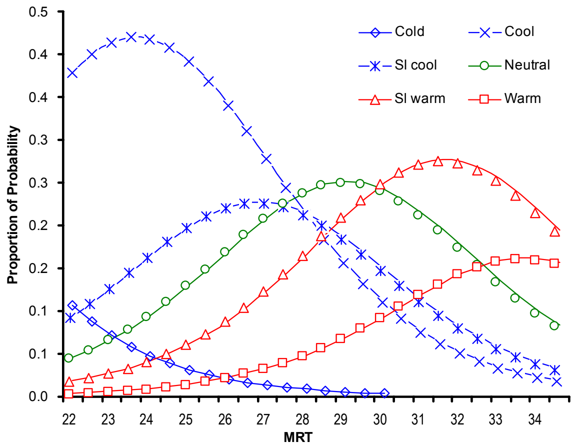

Figure 2: Probit curves for MRT

In general the Y-axis in probit curve shows the proportion of probability of response. The Y-axes values range between 0 to1, with 0 means no (very low) probability and 1 means highest probability (certainty). The X-axis displays the scale (strength, magnitude) of the stimuli. In Figure 1, stimulus of Dry Bulb Temperature (DBT) shows that the highest proportion of probability (curve's peak point) for 'Neutral' response is found at 28.5^0 C. People are likely to perceive the condition as 'Cool' when air temperature reaches about 24^0 C. The response of 'Hot' is not analysed because of very low data captured from the field survey. Figure 2 shows that the maximum probability for 'Neutral' vote is at 29^0 C of MRT. The highest likelihood of people to perceive as 'Warm' is found at 33.5^0 C (MRT). Again here the vote (response) of 'Hot' was not further analysed because of insignificant number of data collected from the field survey. The curve for 'Cold' vote also shows very low probability (about 0.1) at the minimum scale of 22^0 C - MRT.

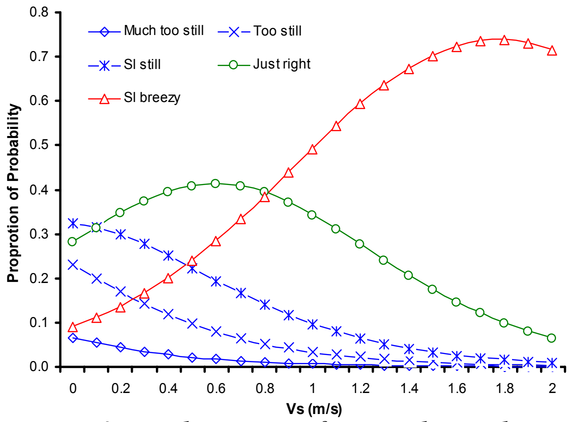

Figure 3: Probit curves for Wind speed

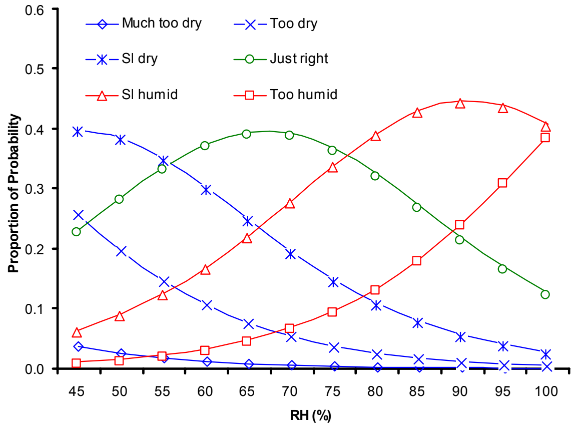

Figure 4: Probit curves for RH

It is shown in Figure 3, from the seven scales of airflow vote, only five scales are selected for Probit analysis. The scales of 'Breezy' and 'Much too breezy' have a very low numbers to allow reliable statistical analysis. The maximum probability of air flow perception of 'Just right' is found at 0.6 m/s. Meanwhile the maximum likelihood of air flow perception for 'Slightly breezy' is found at 1.8 m/s. The Probit curves for other three scales (Slightly still, Too still and Much too still) were similar and only show differences on probability values.

The Probit analyses were also applied within RH stimulus range of 45 – 100%. In Figure 4, the maximum probability of humidity perception of 'Just right' is found at 65% RH. Meanwhile the maximum likelihood for 'Slightly humid' is found at 90% RH. The Probit curves for other two scales (Slightly dry and Too dry) demonstrate the peak at 45% RH. The curve of 'Much too dry' is relatively flat in shape and always below 0.1 value of probability.

MODELLING

Figure 5 displays the schematic diagram of conceptual modelling of TC perception using Fuzzy Logic. First step in the modelling is called ***fuzzification***, which defines linguistic variables, term and membership functions. Originally the concept of linguistic variable was used as an approach to capture natural expressions commonly used by human [Zadeh 1965, 1975]. The second step is called ***fuzzy rule inference*** whereby some sets of fuzzy logic operators and production rules are defined. The final step in modelling is ***defuzzification*** process which aggregates output fuzzy sets to a single number (crisp value).

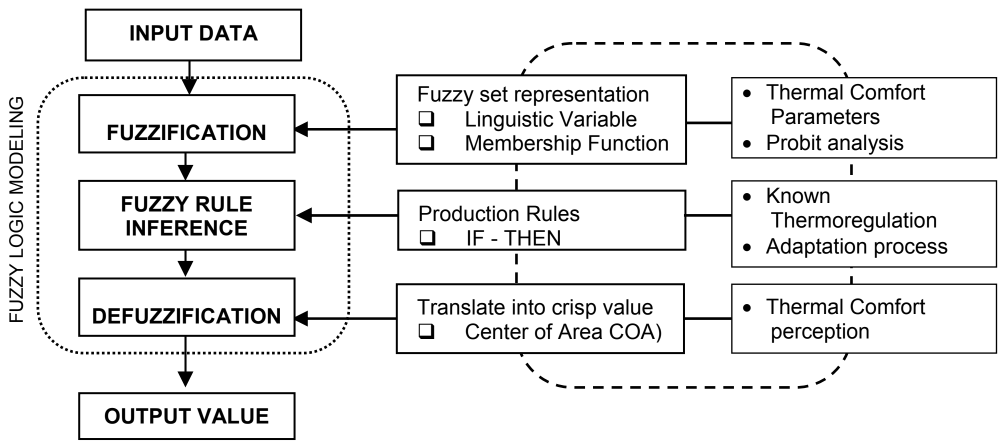

Figure 5: Conceptual fuzzy logic modelling for thermal comfort

Fuzzification

The degree to which crisp value belongs to a given fuzzy set is represented by function known as a membership function (MF). The MF is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The previous sections had presented the effectiveness of probit analysis to generate useful information about people response to particular environmental stimulus (see Figure 1 to 4). The above statistical results are used as basis in defining MF in fuzzification process. The transformation from probit analysis into MF are based on the following considerations,

- The proportions of probability in probit curve are considered as fuzzy set inputs which inform about the partial membership in them.
- The highest values of probability in probit curves correspond to the maximum degree of membership values in fuzzy sets. It is believed that the maximum value of likelihood of perception votes (outcomes) basically indicates the highest degree of memberships (1).
- The probit curve shapes are best represented by Gaussian distribution functions (curves) in the programming of MF using Mathlab® software.

The X-axis input variable for DBT and MRT is $20^0 – 40^0$ C in order to include wider range of possible temperature in the tropics. Figure 6 - 9 depicts membership function plots for DBT, MRT, RH and Wind speed.

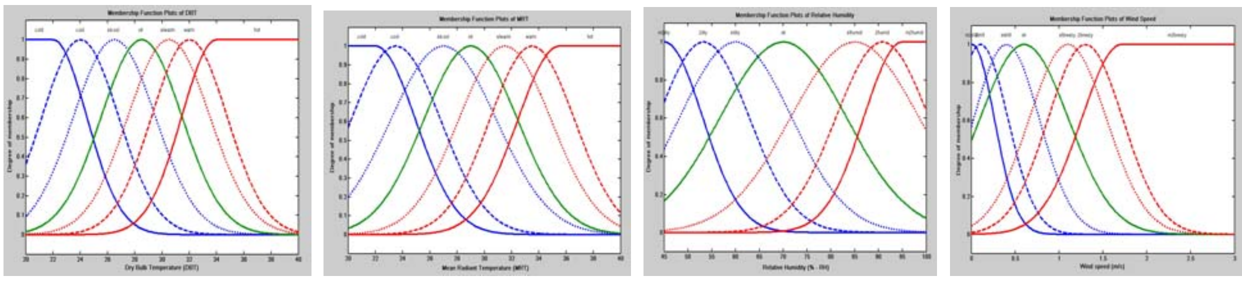

Figure 6 - 9: Membership function plots of DBT, MRT, RH and Vs

Fuzzy Inference

Central to this theory is the concept of the fuzzy IF-THEN rule, which is a mathematical interpretation of the linguistic IF-THEN rule. Production rules consist of precondition (IF-part) and a consequence (THEN-part). The IF-part consist of more than one precondition linked together by linguistic conjunctions like AND and OR. The conjunction AND for MINimum and OR for MAXimum is applied in modelling application [Nguyen et.al 1999]. Total numbers of possible rules based on input variables and linguistic variables is more than 720 combinations of rules. It is impractical and unnecessary to include all the possible rules in the modeling. This model uses 14 rules which are believed to be sufficient to reflect the human thermoregulation of people living in the tropical NV buildings (Table 1).

Table 1: Fuzzy If-Then Rules

Fuzzy IF-THEN Rules									
		Antecedents (Precondition)							Consequents
Rules		DBT	MRT	RH	Wind	Met	Clothing		Feel (sensation)
1	if	Cold	Cold	Much too dry	Slightly still	Low	Thin	then	Cold
2	if	Cold	Cold	Too dry	Slightly breezy	Slightly Low	Slightly thin	then	Cold
3	if	Cool	Cool	Slightly dry	Too breezy	Slightly high	Slightly thin	then	Cool
4	if	Cool	Cool	Just right	Slightly breezy	Slightly low	Thin	then	Cool
5	if	Slightly cool	Slightly Cool	Slightly dry	Just right	Medium	Slightly thin	then	Slightly cool
6	if	Slightly cool	Slightly Cool	Just right	Slightly breezy	Medium	Average	then	Slightly cool
7	if	Neutral	Neutral	Just right	Slightly breezy	Slightly high	Slightly thin	then	Neutral
8	if	Neutral	Neutral	Just right	Just right	Medium	Average	then	Neutral
9	if	Slightly warm	Slightly warm	Too humid	Too breezy	Slightly high	Average	then	Slightly warm
10	if	Slightly warm	Slightly warm	Slightly humid	Slightly still	Medium	Slightly thin	then	Slightly warm
11	if	Warm	Warm	Too humid	Slightly still	Slightly high	Slightly thick	then	Warm
12	if	Warm	Warm	Much too humid	Too still	Medium	Average	then	Warm
13	if	Hot	Hot	Much too humid	Too breezy	Slightly low	Thin	then	Warm
14	if	Hot	Hot	Much too humid	Too still	High	Thick	then	Hot

The following graphs show the dynamic combination of two inputs in affecting TC perception. Figure 10 presents a three-dimensional (3-D) curve which represents the mapping from MRT and DBT as inputs (axis X and Y) and 'Feel' as an output (axis Z). Figure 11 displays the dynamic correlation of wind speed (Vs) and DBT on thermal comfort perception.

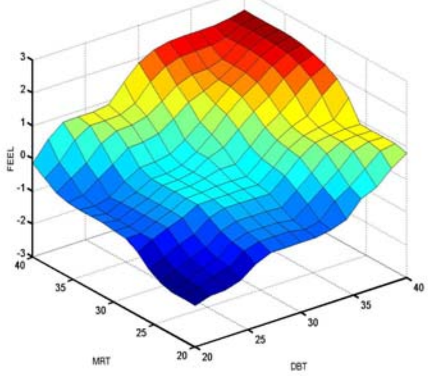

Figure 10: 3-D curve of MRT and DBT

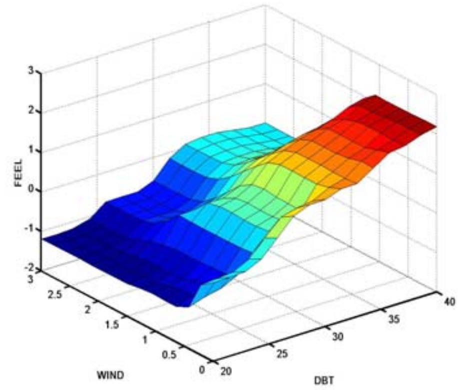

Figure 11: 3-D curve of Vs and DBT

Defuzzification

The result produced from the evaluation of fuzzy rules is, of course, fuzzy. MF are used to retranslate the fuzzy output into a crisp value. This translation is known as defuzzification and can be performed using several methods. The method adopted in this model is Centre of Area (COA) Defuzzification Technique. This method is also known as centre of gravity or centroid defuzzification. This is the most widely used technique and is proven to be reliable in this study. The COA defuzzification technique can be expressed as:

$$x^* = \frac{\int \mu_i(x)x \quad dx}{\int \mu_i(x)dx}$$

Where x^* is the defuzzified output, μ_i *(x)* is the aggregated membership function and *x* is the output variable. The diagram of the whole computational fuzzy modelling is presented in Figure 12. The COA defuzzification is applied to the output area (black curve in right bottom of the diagram) to transform the final output into single number (predicted comfort vote).

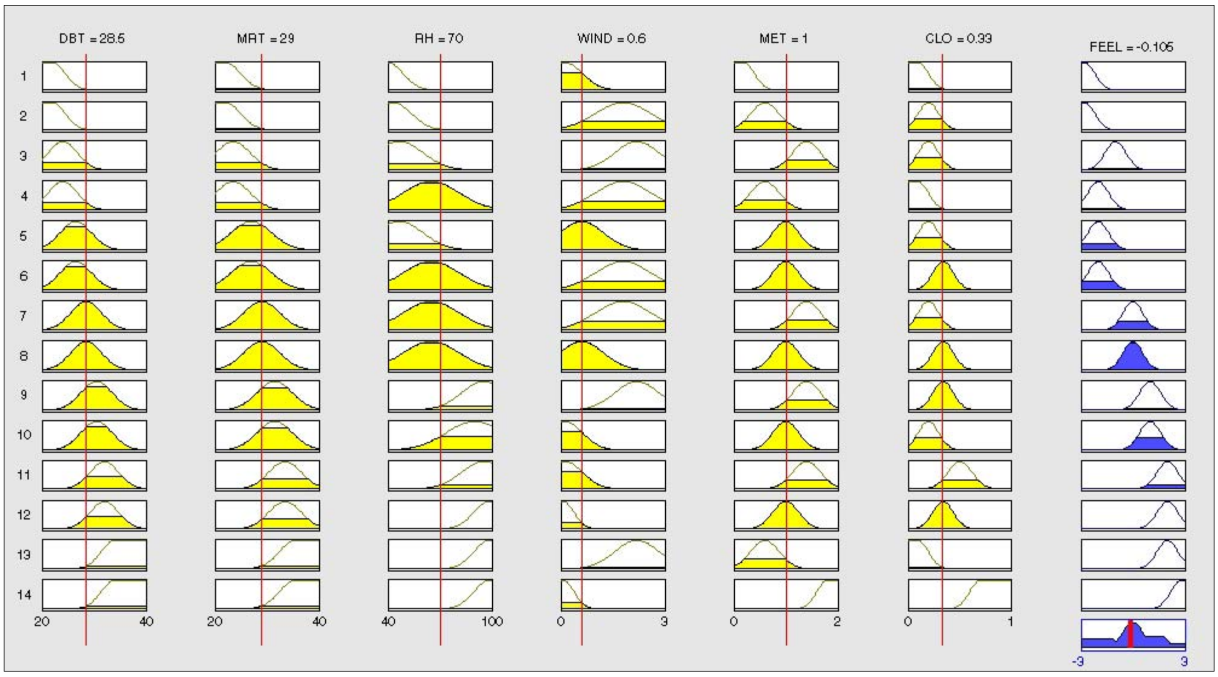

Figure 12: Fuzzy rule views

MODEL VALIDATION

Finally, it is necessary to validate the output by using different set of survey data (200 samples) to demonstrate the robustness of fuzzy logic TC prediction model. Similar to PMV result, the model uses the six parameters of thermal comfort as inputs and computes the prediction votes (number based on 7 points of ashrae scale). The outputs were compared to the actual survey votes and the plot result is presented in Figure 13.

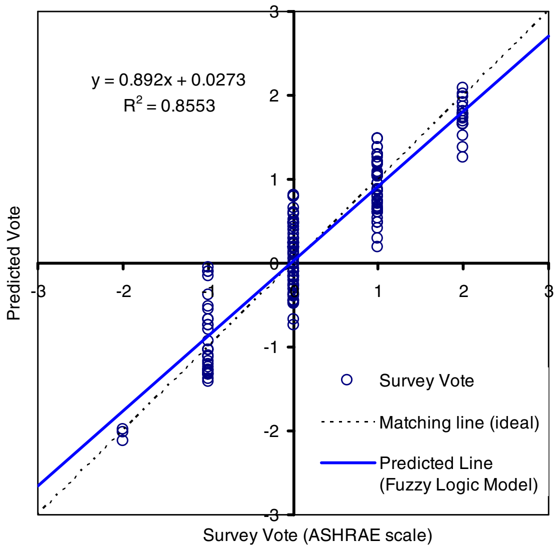

Figure 13: Model validation

Prediction votes based on fuzzy logic modelling has demonstrated a very good correlation with the actual survey votes (R^2=0.9035). Therefore the model may be applied in the future to predict more accurately TC perception in tropical NV buildings. Nevertheless, some discrepancies are still observed due to some reasons:

- The actual survey vote is discrete number (based on 7 scales) meanwhile the predicted output is continuous (not discrete) number.
- The facts that survey votes are naturally based on subjective (personal) human perceptions which vary between persons.

CONCLUSIONS

Fuzzy Logic concept is found to be suitable to model human imprecise linguistic variable in TC perception. The Probit analysis is used to examine the probability of human response under different environmental conditions and to provide fundamental information for developing MF in fuzzification process. The proposed model has shown a good accuracy for predicting TC perception of the occupants in residential NV buildings in the tropics. Further application for NV buildings with different functionality (office, schools etc) requires further validations and this will be the focus of model development in the near future.

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