

## Personalizing Thermal Comfort in a Prototype Indoor Space

Sotirios D Kotsopoulos, Federico Casalegno

School of Humanities Arts and Social Sciences  
Massachusetts Institute of Technology  
Cambridge, Massachusetts, USA  
e-mail: skots@mit.edu, casalegno@mit.edu

Antoine Cuenin

Department of Energy Systems Engineering  
Ecole Nationale Supérieure des Mines  
Nantes, France  
e-mail: antoine.cuenin@gmail.com

**Abstract**—This paper presents an experimental method for monitoring and regulating thermal comfort at the interior of a house. It presents a function that was developed in MATLAB, aiming to compute the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indexes. Furthermore, an improvement of the MATLAB function was developed in the form of a Simulink simulation by using fuzzy logic. Although the method, at its current stage of development, cannot compute a PMV index value in the way it was intended, it does compute the operative temperature, allowing the residents to ascertain whether or not thermal comfort can be established in a particular indoor area.

**Keywords**—thermal comfort; simulation; fuzzy logic.

### I. INTRODUCTION

Thermal comfort is of paramount importance in ensuring fine living conditions in indoor spaces. This paper presents an experimental method for monitoring and regulating thermal comfort at the interior of a prototype house that is at the final stage of construction in Trento, N. Italy. The theory of thermal comfort is used, based on the work of P. O. Fanger who introduced two indexes, the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), in order to quantify the parameter of thermal comfort [1]. This study presents a function that was developed in MATLAB [2] to compute thermal comfort based on simulation. The function computes the PMV and PPD indexes at the same time and displays the results on a graph. Furthermore, an improvement of the MATLAB function was developed in the form of a SIMULINK simulation [3] by using fuzzy logic [4]. Although the overall system at its current stage cannot compute a PMV index value in the way it was intended at the beginning of the research, it does compute the operative temperature, thus allowing the residents to ascertain whether or not thermal comfort can be established in a particular indoor house area.

Numerous attempts to quantify thermal comfort have been made since the 1970's, when the Danish scientist P.O Fanger established a thermal comfort theory. Although Fanger published his first paper on the subject with the intention to establish a higher standard for the use of Heating Ventilating and Air Conditioning (HVAC) systems, the theory of thermal comfort was neglected by the environmental management industry. The approach of

traditional environmental management systems towards indoor comfort relies mostly on tracking the fluctuation of the interior temperature and humidity levels and reactively adjusting the operation of the HVAC system. This approach is not different from using simple thermostatic control. Furthermore, traditional environmental management systems regulate the thermal conditions of an interior at a building scale and individual considerations are neglected.

The design philosophy of the prototype house in Trento aims at a personalized environmental management approach [5], [6]. The south façade of the prototype is a programmable solar wall, forming a grid of electro-active windows, the modifications of which enable the precise adjustment of light, heat, view, and air in the interior. On a hot summer day, the electrochromic layer of a number of windowpanes can be set to its minimum solar transmittance value to protect the interior from direct sun exposure. On a cold winter day, it can be set to its maximum solar transmittance value to expose the interior to the winter sun. One of the project's objectives is to minimize the use of electricity. The residents determine the desired comfort levels and their schedules, and a central control system minimizes the consumption of electricity while guaranteeing that the comfort levels are maintained at all times. Given that the Trento prototype was envisioned to provide an environment that remains adaptable to individual human needs, it was only natural to attempt developing an environmental management system that would acknowledge the thermal comfort level of individual users.

After providing a brief overview of related work to this research, a MATLAB function is presented able to calculate the thermal comfort levels at the interior of the prototype house. After presenting simulations with the MATLAB function, tools involving fuzzy logic are integrated in the method of computing the PMV and PPD values, aiming to provide greater flexibility and accuracy in the calculations. The system that is presented in the paper combines two parts operating in parallel, a *personal-dependent model* and an *environmental model*. A series of calculations of the PMV index are presented next, with the motivation to prove that the proposed system in its current state, while not fully operational, it is still competent. It simulates PMV and in real life application it can supply a temperature that is in close proximity to the one that achieves thermal comfort. Finally, the paper ends with the conclusions and with suggestions for further research.

## II. BACKGROUND

Thermal comfort accounts for numerous parameters that influence decisively a person's feeling of comfort in an indoor space. Multiple atmospheric parameters have to be considered if one is to determine the thermal comfort in a room, namely, *air temperature*, *mean radiant temperature*, *air velocity*, and *relative humidity*. *Mean radiant temperature* is the uniform temperature of the surrounding surfaces, which will result in the same heat exchange by radiation from a person as in the environment. *Air velocity* is a parameter that is relevant to the consideration of the heat loss by convection. *Air velocity* is directly related to the amount of energy exchanged in this physical process. *Relative humidity* is an important aspect of the global heat loss process. If the air is dry the *relative humidity* is low, and perspiration increases to help keep the body cool. A high level of *relative humidity* will prevent perspiration, and it will have the opposite effect of a low *relative humidity*.

Thermal comfort is based on the notion of the human body heat balance. The human body produces energy and heat that is required for its operation by burning calories. When there is a balance between heat production and heat loss, the body's temperature is at 37 °C and Fanger's equation is satisfied:

$$S = M \pm W \pm R \pm C \pm K - E - RES = 0. \quad (1)$$

where:

- S = Heat Storage
- M = Metabolism
- W = External work
- R = Heat exchange by radiation
- C = Heat exchange by convection
- K = Heat exchange by conduction
- E = Heat exchange by evaporation
- RES = Heat exchange by respiration

*Metabolism* represents the amount of heat released inside the human body once calories have been burned. *Heat loss by evaporation* accounts for the body heat loss by the diffusion of water through the skin. This water uses body heat to evaporate, thus contributing to heat loss. *Heat loss through clothing* accounts for the heat exchange of body heat with the external environment by diffusion, through clothes. Clothes worn by a person affect the amount of the exchanged heat. Experiments with thermal mannequins in thermal chambers had determined the thermal insulation provided by clothes [7]. *Heat loss by radiation* amounts to the heat exchange of the body with its surroundings through radiation. *Heat loss by convection* corresponds to one of the major modes of heat transfer. The heat is "carried away" by the airflow. The amount of heat exchanged depends on the air velocity. The *air velocity* determines whether or not the convection is "free" or "forced".

To calculate the degree of thermal comfort within a group of people, Fanger devised the PMV index. The PMV is calculated by Fanger's comfort equation (1). Each time the equation is satisfied under specific conditions, a large group of people experience thermal neutrality, or thermal comfort.

Table I presents the seven-level scale that the PMV index employs to capture the mean thermal sensation vote of a group of people.

TABLE I. PMV SEVEN-LEVEL SCALE

Scale	Feeling
-3	Cold
-2	Cool
-1	Slightly cool
0	Neutral
1	Slightly warm
2	Warm
3	Hot

The PMV model indicates the level of thermal comfort for a group of healthy adults. It is a statistical estimation of the mean thermal comfort and hence some individuals may still feel uncomfortable even in cases that the PMV index equals zero. The PPD index describes the percentage of occupants that are dissatisfied with the given thermal conditions. Statistical data show 5% PPD is the lowest percentage of dissatisfied practically achievable since providing an optimal thermal environment for every single person is not possible. Even though the PMV model works well for adults it requires adjustment for older adults, children and disabled people. Feldmeier [8] demonstrated that using the PMV index is not the best way to calculate thermal comfort. Fanger was aware of the limitations and shortcomings of his model. He advised careful use of the PMV index for values below -2 and above +2. He also warned that the results of the PMV model should be regarded as a first estimation. In practice, while the PMV index has been validated by field studies, these studies pointed out that PMV index should be used with caution when dealing with small groups of people. One of the problems of the PMV index results from the fact that the theory was developed in precisely controlled and monitored environments. Certain values such as clothing insulation that can be easily determined in the context of the experiments are difficult to determine in a real life applications.

International norms and standards provide guidelines regarding the regulation of thermal comfort. Three main guidelines exist, namely, the International Organization for Standardization ISO EN 7730 – 2005a, the American Society of Heating, Refrigerating and Air-Conditioning Engineers ASHRAE Standard 55 – 2004, and the European Committee for Standardization CEN CR 1752. All three provide recommendations based on the PMV index determined by Fanger. Thermal comfort is achieved when  $PPD \leq 10\%$  and  $-0,5 \leq PMV \leq 0,5$ . It is recommended that no local thermal discomfort factors such as radiant temperature asymmetry, vertical air temperature difference, floor surface temperature, temperature variation with time, etc. are in effect. The standard for thermal comfort is defined by the operative temperature. The operative temperature is defined as a uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. The operative temperature intervals vary by the

type of indoor location and by the time of year. ASHRAE standards [9] have listings for suggested temperatures and air flow rates in different types of buildings and different environmental circumstances. Moreover, to overcome the limitations of the PMV index, ASHRAE [9] introduced a new adaptive model for measuring thermal comfort. The adaptive hypothesis predicts that contextual factors and past thermal history modify building occupants' thermal expectations and preferences. The ASHRAE-55 2010 Standard has introduced the *prevailing mean outdoor temperature* as input variable for the adaptive model. It is based on the arithmetic average of the mean daily outdoor temperatures (DBT) over no fewer than 7 and no more than 30 sequential days prior to the day in question. This model applies especially to occupant-controlled, natural conditioned spaces, where the outdoor climate can actually affect the indoor conditions and so the comfort zone. Studies by de Dear and Brager [10] showed that occupants in naturally ventilated buildings were tolerant of a wider range of temperatures. ASHRAE Standard 55-2010 states that differences in recent thermal experiences, changes in clothing, availability of control options and shifts in occupant expectations can change people thermal responses. The new model is proposed alongside Fanger's PMV index in every release of ASHRAE Standard 55, however, it has been also ignored by the majority of the HVAC industry.

Further research on thermal comfort considers the heat balance of the human body and calculates sensation and comfort for local body parts [11], [12].

### III. PMV AND PPD CALCULATIONS

A MATLAB function was devised to calculate the thermal comfort levels at the interior space of the prototype house. The motivation driving these calculations was to understand the thermal conditions at the house interior on a specific day of the year, based on specific assumptions. The function that calculates thermal comfort contains two parts, namely, the main PMV function named PMV.m., and the ComputeTCL.m function. The PMV.m. function collects the values of the activity, the clothing insulation, the air temperature, the mean radiant temperature, the relative humidity, the air velocity, and the external work. Moreover, PMV.m. has as task to: compute all the necessary values that are needed in order to calculate the PMV and PPD values, call the ComputeTCL.m function to compute the numeric value, and display the PPD on a graph. The ComputeTCL.m function calculates iteratively the clothing temperature value. In the next calculations the values for the metabolism, the insulation induced by the clothes, and the interior air velocity, were provided. The simulation experiments were run for the hottest day of the year, July 15<sup>th</sup>, in N. Italy assuming that the activity of the person was light and that the person was wearing light clothes such as a pair of shorts and a light shirt. The air velocity was set to the one recommended by the ASHRAE for optimum indoor comfort.

Table II presents the conditions of the experiments I, II, III and IV.

TABLE II. CONDITIONS OF EXPERIMENTS I, II, III, IV

Parameter	I	II	III	IV
Air temperature (C°)	35	24	43	24
Mean radiant temperature	35	30	43	33
Relative humidity (%)	46	55	30	53
Clothing index (Clo)	0.6	0.6	0.6	0.6
Metabolism (W)	70	70	70	70
Air velocity (in m.s <sup>-1</sup> )	0.15	0.15	0.15	0.15

#### A. Experiment I

In the first experiment, the thermal comfort was computed for the hottest day of the year, July 15, at 2:00 PM, in N. Italy assuming that the electrochromic material of the windows was active and the AC system was inactive. Based on the values of Table II, the results were PMV=3 and PPD=100. A plot of the PPD (PMV) appears in Figure 1.

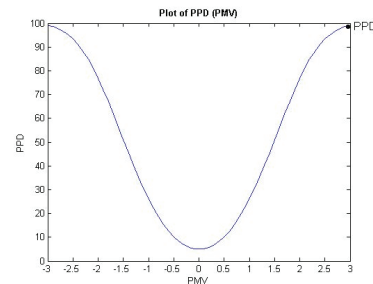


Figure 1. Plot of PPD (PMV) for experiment I.

#### B. Experiment II

In the second experiment, the thermal comfort was computed for the hottest day of the year, July 15, at 5:00 PM, in N. Italy assuming that the electrochromic material of the windows was active and the AC system was active, too. Based on the values of Table II, the results were PMV=0.17 and PPD=5.6. A plot of the PPD (PMV) appears in Figure 2.

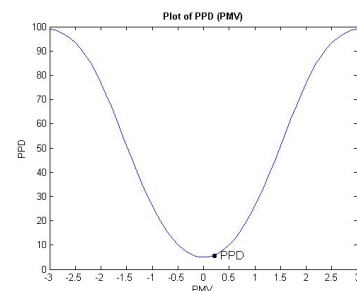


Figure 2. Plot of PPD (PMV) for experiment II

#### C. Experiment III

In the third experiment, the thermal comfort was computed for the hottest day of the year, July 15, at 2:00 PM, in N. Italy assuming that the electrochromic material of the windows was inactive and the AC system was inactive, too.

Based on the values of Table II, the results were  $PMV=3$  and  $PPD=100$ . A plot of the PPD (PMV) appears in Figure 3.

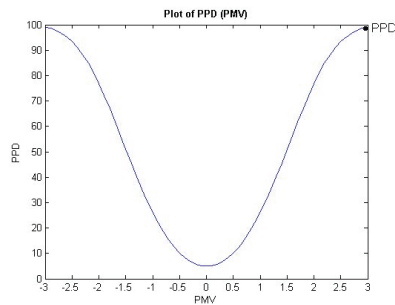


Figure 3. Plot of PPD (PMV) for experiment III.

#### D. Experiment IV

In the fourth experiment, the thermal comfort was computed for the hottest day of the year, July 15, at 5:00 PM, in N. Italy assuming that the electrochromic material of the windows was inactive and the AC system was active. Based on the values of Table II, the results were  $PMV=0.47$  and  $PPD=9.6$ . A plot of the PPD (PMV) appears in Figure 4.

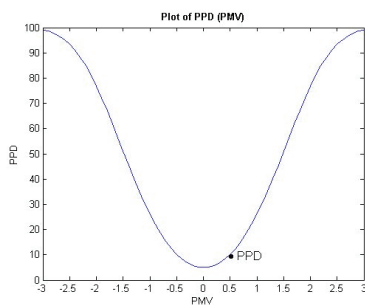


Figure 4. Plot of PPD (PMV) for experiment IV.

The calculations I, III – performed during different time of the day – allow the comparison of performance with and without activating the electrochromic windows. The results indicate an improvement when the electrochromic windows are active, but in both calculations I, III the thermal comfort is far from being achieved. In calculations II and IV, the HVAC system is active. This allows evaluating the impact of a modern HVAC system during the hottest day of the year. In both cases II, IV the PPD value is sufficiently low and statistically 90 % of people will experience thermal comfort.

In the experiments I, II, III and IV, thermal comfort is computed during the most demanding weather conditions. Given that the goal of the prototype house in Trento was not to perform as a passive house, but rather as a low consumption one, even with the parallel operation of an HVAC system, this goal is still attainable. Furthermore, Fanger recognized that the PMV model is not infallible for values superior to +2. In the light of these findings, further study was conducted to allow for a wider spectrum of possible models to offer more accurate account of thermal comfort.

## IV. FUZZY LOGIC CONTROLLER

After performing simulations with the MATLAB function, the methods of the calculation were upgraded. More specifically, tools involving fuzzy logic were intergraded to compute the PMV and PPD values with greater flexibility and accuracy. The idea to use a simulation tool based on fuzzy logic originates from a paper by J. van Hoof [13]. Unlike Boolean logic, fuzzy logic allows for additional states than *true* or *false*. The core of the fuzzy logic theory is the membership function. A membership function (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 fuzzy logic PMV controller was first discussed in Hamdi et al. [4]. The paper points to several advantages of a fuzzy logic controller compared to other methods. One of the main problems regarding Fanger's PMV model is that his equations are not linear and hence they are unsuitable for a feedback control system [14], [15]. A lot of effort has been made to find a way around the iterative process of calculating the value of the temperature of clothing [16], [17], [18], by simplifying the equations. However, researchers pointed out that such simplifications in the PMV model made it unreliable and subject to errors [15]. Hamdi et al. [4] proposed a way of computing the PMV index accurately without having to use the iterative process. The proposed fuzzy logic controller is based on [4].

The next sections expose the attempt of integrating fuzzy logic in our thermal comfort controller. The main advantages of using fuzzy logic to compute the PMV index of a particular dataset are the use of a non-iterative process that is appropriate for feedback control, the real time simulation capability, and the great accuracy. MATLAB was used again to implement the fuzzy PMV index described in [4]. MATLAB includes a built-in fuzzy logic toolbox that can interact with the SIMULINK environment through a specially designed block, namely, the fuzzy controller block. SIMULINK is built-in the MATLAB environment and can either drive or be scripted from it. It was decided to use the environment for its tight integration with MATLAB, and therefore with the fuzzy toolbox. An additional reason for selecting SIMULINK was the existence of a block library for fuzzy logic. By providing a graphical simulation tool, SIMULINK made the development easier and allowed the simulation of dynamic systems. The final system combines two parts working together to compute the PMV index value, a *personal-dependent model* and an *environmental model*.

### A. Personal-Dependent Model

The personal-dependent model takes into consideration only the variables depending on a person inside a room. There are only two inputs for this part of the system, the metabolic activity of the person in question, and his or her clothing index (i.e., clothing insulation). The output of this subsystem is a temperature value contained in a range of temperatures within which stands the operative temperature. The operative temperature is the required temperature to reach a PMV value equal to 0 when the air temperature equals to the mean radiant temperature ( $T_{air} = T_{mrt}$ ) and



$RH=50\%$ . The “fuzzy Personal-Dependent Model” block of Figure 5 contains a set of membership functions and their associated rules. Its output is the air temperature range in which the PMV is found to be close to zero. It returns a value contained in a specific range.

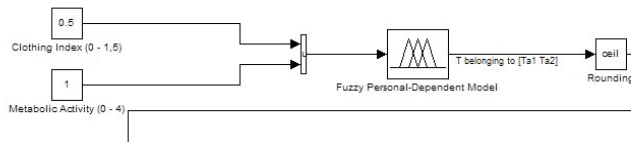


Figure 5. Diagram of the personal-dependent model in SIMULINK

Given that the various temperature intervals are fixed and do not overlap, knowing a specific value provides access to the temperature range in which the value is contained. The purpose of the block immediately following the fuzzy controller block is to round up the output value of the preceding block in order to use this value in the next block (i.e., the switch block) which accepts only integers.

### B. Environmental Model

While the personal-dependent model is complete, the environmental model is not yet fully operational. Figure 6 presents the block diagram of the environmental model in its current state of development. When completed, this model will be fairly complex. The first block of the environmental model is a “switch block” that allows the system to select between five different temperature ranges, depending on the unique value returned by the first subsystem.

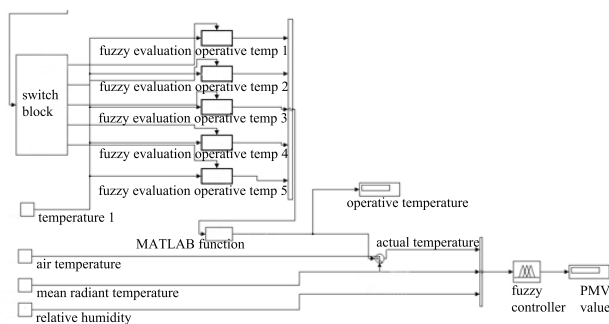


Figure 6. Block diagram depicting the environmental model in its current state of development.

Each block in the middle of the model is a subsystem that contains a fuzzy controller, an input and an output. Figure 7 illustrates a block of this kind.

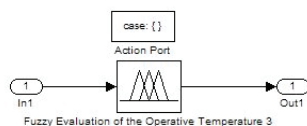


Figure 7. Block diagram depicting a specific subsystem.

Depending on the input value in the “switch block”, the corresponding subsystem representing the correct air temperature range is triggered. The input value of each fuzzy controller is the air velocity. In the current state of the system, it is considered constant, but it can be upgraded to produce a signal mimicking the air velocity variations over a period of time. The output value is a temperature displayed in a display block and named “operative temperature”. The last block is a MATLAB function (.m function) designed to extract the only positive value contained in the vector created on the right of the five subsystem blocks. In this fashion the system can deal with a number instead of a vector containing five components.

### C. Membership Function of Personal-Dependent Model

Each fuzzy controller block is embedded in the overall system with a membership function created with the MATLAB fuzzy logic toolbox. The membership functions are identical to the ones described in [4]. Figures 8, 9 and 10 exhibit the membership functions used in the personal-dependent mode of the controller.

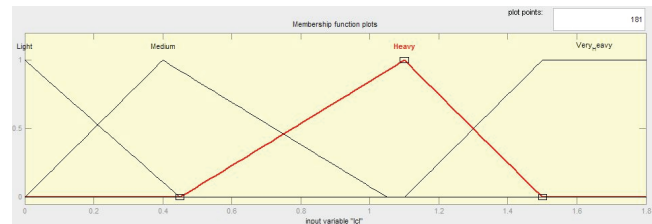


Figure 8. Membership functions of the clothing insulation.

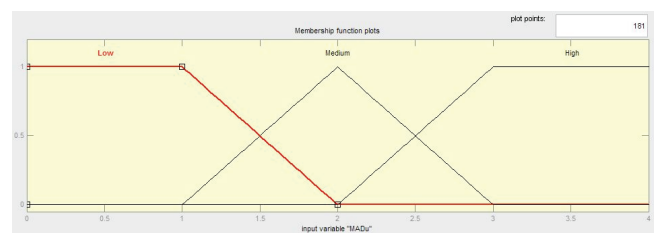


Figure 9. Membership functions of the metabolic activity.

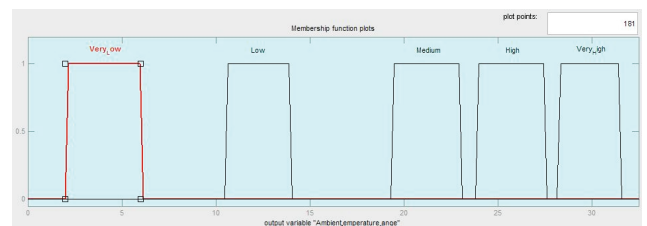


Figure 10. Membership functions of the temperature range.

In the above illustrations of the membership functions of the air temperature range, five temperature intervals are noticeable. The fuzzy controller returns a temperature value as output. Selecting the temperature range within which this value falls is doable since none of the temperature intervals are overlapping. Figure 11 presents the output surface of the

personal-dependent model and visualizes the interaction between the two inputs.

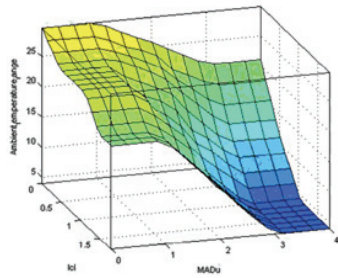


Figure 11. Output surface of the personal-dependent model.

A set of fuzzy rules permits the interaction of the membership functions of the personal-dependent model. Table III presents these rules.

TABLE III. FUZZY RULES OF THE PERSONAL-DEPENDENT MODEL

If  c  is      and MADu is      then Ambient_temperature_range is		
1.	If ( c  is Light) and (MADu is Low) then (Ambient_temperature_range is Very_High (1)	
2.	If ( c  is Light) and (MADu is Medium) then (Ambient_temperature_range is High (1)	
3.	If ( c  is Light) and (MADu is High) then (Ambient_temperature_range is Medium (1)	
4.	If ( c  is Medium) and (MADu is Low) then (Ambient_temperature_range is High (1)	
5.	If ( c  is Medium) and (MADu is Medium) then (Ambient_temperature_range is Medium (1)	
6.	If ( c  is Medium) and (MADu is High) then (Ambient_temperature_range is Low (1)	
7.	If ( c  is Heavy) and (MADu is Low) then (Ambient_temperature_range is High (1)	
8.	If ( c  is Heavy) and (MADu is Medium) then (Ambient_temperature_range is Low (1)	
9.	If ( c  is Heavy) and (MADu is High) then (Ambient_temperature_range is Very_Low (1)	
10.	If ( c  is Very_Heavy) and (MADu is Low) then (Ambient_temperature_range is Medium (1)	
11.	If ( c  is Very_Heavy) and (MADu is Medium) then (Ambient_temperature_range is Low (1)	
12.	If ( c  is Very_Heavy) and (MADu is High) then (Ambient_temperature_range is Very_Low (1)	

Figure 12 presents the screen capturing the rule-viewer of the fuzzy logic MATLAB toolbox. The rule viewer displays in a single screen all the parts of the fuzzy inference process from inputs to outputs. Each row corresponds to a single rule and each column corresponds to an input variable (yellow on the left) or an output variable (blue on the right).

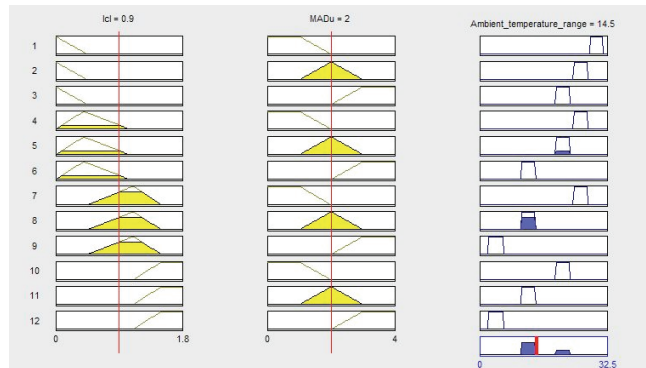


Figure 12. Personal-dependent model rule viewer.

In the case of the environmental model (Figures 13, 14) five fuzzy controllers exist for five temperature ranges. The shapes of the membership functions are identical in each of the cases. The difference resides in the range of the output.

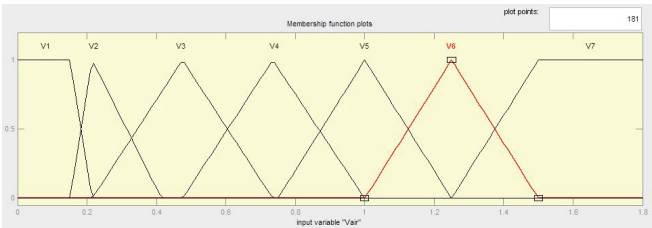


Figure 13. Membership functions of air velocity (environmental model).

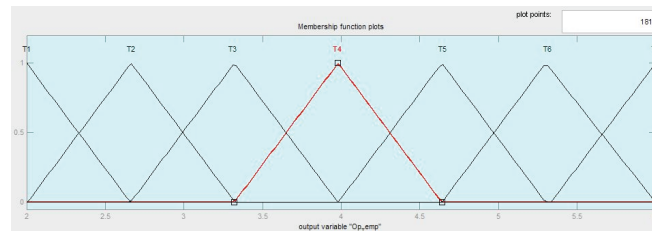


Figure 14. Membership functions of the operative temperature.

The shape of the membership functions is derived from the thermal comfort setting of a user and the interaction of the different parameters. Table IV presents the fuzzy rules of the environmental model that interact with the two previous sets of membership functions.

TABLE IV. FUZZY RULES OF THE ENVIRONMENTAL MODEL

If Vair is      then Op_Temp is	
1.	If (Vair is V1) then (Op_Temp is T1) (1)
2.	If (Vair is V2) then (Op_Temp is T2) (1)
3.	If (Vair is V3) then (Op_Temp is T3) (1)
4.	If (Vair is V4) then (Op_Temp is T4) (1)
5.	If (Vair is V5) then (Op_Temp is T5) (1)
6.	If (Vair is V6) then (Op_Temp is T6) (1)
7.	If (Vair is V7) then (Op_Temp is T7) (1)
8.	If (Vair is V8) then (Op_Temp is T8) (1)

Figure 15 presents the screen capturing the rule-viewer of the sets of membership functions.

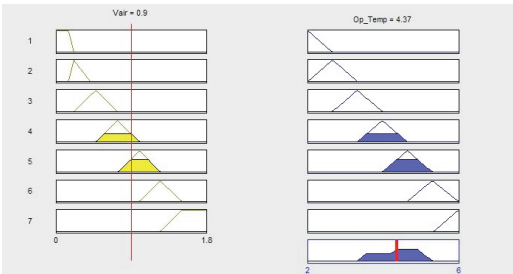


Figure 15. Rule viewer of the environmental model.

#### D. Implementation Remarks

The implementation of the system encountered two major problems. First problem was that it was necessary to compute the exact operative temperature, even though the temperature range from which it is computed varies each time among a set of five temperature ranges. The adopted solution was to use a “switch block”. The “switch block” functions like a switch conditional statement in C#. However, since it accepts only integers as input, this input value is rounded up. Once the value is entered in the “switch block”, the “switch block” triggers the sub-system containing the correct fuzzy controller in which the correct membership functions with the correct temperature range are embedded. Since there is no way to know which of the subsystems is going to be triggered, every subsystem returns a value, that can be zero or the operative temperature. A “mux block” allows the system to create a vector containing five components. Since the system can only deal with a single number from this point, a MATLAB function extracts the number corresponding to the operative temperature. In order to accomplish it, the MATLAB function sums all the components of the vector since they are all equaled to zero except from the only one of interest.

The second problem relates to the environmental model. Once the operative temperature is returned by the system, it is compared with the actual air temperature. The effects of the mean radiant temperature and of the relative humidity are considered to adjust the operative temperature – which must be close to the required temperature – in order to reach a PMV value of zero. The problem resides in the range of the membership functions. In order to adjust the temperature the range of the membership function must be regenerated depending on the value of the operative temperature returned by the first part of the environmental model. No solution has been found for this problem.

#### V. VALIDATION OF THE SYSTEM

The current system cannot compute a PMV index value in the way it was intended. But, it does compute the operative temperature. The operative temperature is the air temperature for which the PMV index approaches zero when  $T_{air} = T_{mrt}$  and  $RH = 50\%$ . According to Chamra et al. [19], clothing insulation, metabolic activity as well as air velocity are the three fundamental parameters that affect thermal comfort. Hence, PMV is more sensitive to these three parameters than to the mean radiant temperature and the relative humidity. To confirm this statement, a series of calculations of the PMV index value were conducted, with the motivation to prove that the system in its current state, while not fully operational is still competent. It simulates PMV and it can supply a temperature close to thermal comfort. The simulations of the Tables V, VI, VII and VIII, follow four assumptions:

- Relative humidity falls rarely below 20% or above 80%.
- Optimum air velocity is  $0,15 \text{ m.s}^{-1}$ .
- Comfort zone is  $-0,5 \leq \text{PMV} \leq 0,5$  and
- Metabolic rate is  $1 \text{ met}$ . Such value is consistent with a

sedentary light activity at a house interior.

The Tables V, VI, VII, and VIII contain the results of the simulations that were performed in order to:

(i) Confirm that the operative temperature yields PMV close to zero if  $T_{air} = T_{mrt}$  and  $RH = 50\%$  with variable clothing insulation.

(ii) Determine the impact of the mean radiant temperature and the relative humidity on the PMV value for  $T_{air} = T_{operative}$ .

TABLE V. RESULTS OF 8 SIMULATION EXPERIMENTS WITH CLOTHING INSULATION = 1 CLO

Parameters	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
Clothing (clo)	1	1	1	1	1	1	1	1
Operative temp. (°C)	24,2	24,2	24,2	24,2	24,2	24,2	24,2	24,2
Mean radiant temp. (°C)	24,2	23,2	22,2	21,2	20,2	19,2	18,2	17,2
Activity (met)	1	1	1	1	1	1	1	1
Air speed (m/s)	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15
Relative humidity (%)	50	50	50	50	50	50	50	50
PMV	0,2	0	-0,1	-0,2	-0,3	-0,4	-0,5	-0,6
PPD	5,8	5	5,2	5,8	6,9	8,3	10,2	12,5

TABLE VI. RESULTS OF 8 SIMULATION EXPERIMENTS WITH CLOTHING INSULATION = 1,5 CLO

Parameters	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
Clothing (clo)	1,5	1,5	1,5	1,5	1,5	1,5	1,5	1,5
Operative temp. (°C)	19,7	19,7	19,7	19,7	19,7	19,7	19,7	19,7
Mean radiant temp. (°C)	19,7	18,7	20,7	21,7	22,7	17,7	16,7	26,7
Activity (met)	1	1	1	1	1	1	1	1
Air speed (m/s)	0,15	0,15	0,15	0,15	0,15	0,15	0,15	0,15
Relative humidity (%)	50	50	50	50	50	50	50	50
PMV	-0,3	-0,3	-0,2	-0,1	0	-0,4	-0,5	0,4
PPD	6,9	6,9	5,8	5,2	5	8,3	10,2	8,3

In all experiments, with the exception of the one presented in the next Table VII, the operative temperature is sufficient to provide thermal comfort when the air temperature equals to the mean radiant temperature ( $T_{air} = T_{mrt}$ ) and  $RH = 50\%$ . In the experiments presented in Table VII, the clothing insulation is  $l_{cl} = 0,5 \text{ clo}$  and thermal comfort is not achieved because the PMV is out of the recommended range. However, it should be kept in mind that still only 22% of people would experience discomfort.

Regarding the influence of the mean radiant temperature, in the worst case, there is a difference of  $3 \text{ C}^\circ$  between the mean radiant temperature for which the PMV equals zero and the mean radiant temperature for which  $\text{PMV} \geq |0,5|$ . This case appears in Table VII in the comparison of the

mean radiant temperature values of Experiment 3 and Experiment 6. This provides a margin of error that makes possible using the system in its present stage of development. According to the simulation data recorded with *Design Builder* software, the mean radiant temperature is always close to the air temperature when the electrochromic windows are activated.

TABLE VII. RESULTS OF 8 SIMULATION EXPERIMENTS WITH CLOTHING INSULATION = 0,5 CLO

Parameters	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6
Clothing (clo)	0,5	0,5	0,5	0,5	0,5	0,5
Operative temp. (°C)	24,2	24,2	24,2	24,2	24,2	24,2
Mean radiant temp. (°C)	24,2	25,2	26,2	27,2	28,2	29,2
Activity (met)	1	1	1	1	1	1
Air speed (m/s)	0,15	0,15	0,15	0,15	0,15	0,15
Relative humidity (%)	50	50	50	50	50	50
PMV	-0,9	-0,7	-0,5	-0,4	-0,2	0
PPD	22,1	15,3	10,2	8,3	5,8	5

TABLE VIII. RESULTS OF 8 SIMULATION EXPERIMENTS WITH CLOTHING INSULATION = 1 CLO AND HIGHER AIR SPEED

Parameters	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8
Clothing (clo)	1	1	1	1	1	1	1	1
Operative temp. (°C)	24,6	24,6	24,6	24,6	24,6	24,6	24,6	24,6
Mean radiant temp. (°C)	24,6	27,6	23,6	22,6	21,6	18,6	22,6	22,6
Activity (met)	1	1	1	1	1	1	1	1
Air speed (m/s)	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2
Relative humidity (%)	50	50	50	50	50	50	0	100
PMV	0,2	0,6	0,1	0	-0,1	-0,5	-0,4	0,4
PPD	5,8	12,5	5,2	5	5,2	10,2	8,3	8,3

Regarding the impact of the relative humidity on the PMV value when  $T_{air} = T_{mrt}$ , in all cases except one, the PMV stays within the boundaries of thermal comfort  $PMV \leq [0,5]$ . These cases are depicted in Experiment 1 of each of the above Tables, where relative humidity  $RH = 50\%$ . The exception appears in the Experiment 1 of Table VII, where  $PMV = -0,9$ . These results reveal that although relative humidity does affect PMV, its effect is not critical.

## VI. CONCLUSION AND FUTURE WORK

The objective of this study is to produce a system for personalizing thermal comfort at the interior of a prototype house in Trento, N. Italy. A MATLAB function was developed to compute the PMV and PPD values from a given dataset. A first set of calculations during the hottest day of the year proved that the house would provide

uncomfortable interior conditions for most people whether or not its electrochromic windows are active. The same calculations also proved that the HVAC system would contribute to the achievement of thermal comfort in the house interior. In order to enhance the accuracy of the thermal comfort calculation and to offer dynamic features, fuzzy logic was used. Fuzzy logic allows computing the PMV in real time thus enhancing the attractiveness of the system for real life application. While the overall system cannot compute a PMV index value as it was intended at the beginning, the development of the thermal comfort controller is still in progress, and the system – given the proper data – produces a correct operational value of thermal comfort for the interior of the prototype. This temperature can be used to adapt the thermal comfort with accuracy.

SIMULINK was used for the graphical interface of the system, to make the design and the implementation of the system less complex. The actual code was also generated by SIMULINK providing the opportunity to further develop the proposed experimental apparatus in a real life system. To that effect, a built-in module for SIMULINK called Real-Time Workshop generated the C code equivalent to the system built with blocks in the graphical interface.

While this paper addressed the development of a computational apparatus calculating the thermal comfort of a person, it does not touch upon the implementation of an actual house system. The development of such a system that computes thermal comfort is in progress. The next steps of this research will be to complete the environmental subsystem and adjust the membership functions in order to obtain better accuracy. Once the environmental subsystem is completed, some further improvements could be made in order to fully take advantage of the possibilities offered by the MATLAB and the SIMULINK environment. Possible enhancements may include adding a feedback loop that would make the system adaptive. Adding a neural network would make the system capable of learning the preferences of its users [20], thus transforming the fuzzy PMV system into a neuro-fuzzy PMV system. Furthermore, it is possible to use signal generators instead of using constant values as inputs. This would take advantage of the capability of SIMULINK for conducting dynamic simulations, thus providing insights on how the PMV and the operative temperature vary during a certain period of time. Experimenting with different membership functions could be another option. Triangular functions were used in the current implementation. The use of Gaussian or polynomial based membership functions could contribute to better accuracy.

Finally, since the calculation of the PMV index value is based on statistics there are no guarantees that the thermal conditions decided by the computer will satisfy the inhabitants. Nonetheless, the proposed model can predict what the end user will be expecting. To radically improve the system, this must be paired with a learning capacity. Then given time and feedback, the system will learn from the end-user experience, and refine the PMV model to accommodate the needs of the inhabitants. In order to learn and adapt based on the requirements of the users, the computer will have to



collect feedback data. And the error margin will decrease, as the user's inputs will be stored into the system.

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