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Enriching Empirical Thermal Comfort Assessment Methods with Fuzzy Logic

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Abstract

Building occupants spend approximately 90% of their lives indoors where they want to have indoor air quality, visual, acoustic, and thermal comfort (which is more dominant). Thermal comfort is assessed by physical factors such as operative air temperature, relative humidity, and air velocity. People's activity level and clothing level are also effective. Related regulations and standards like ISOEN7730 and EN15251 aim to provide a unified understanding of the matter. Since these studies rely on experimental methods, there are instances where certain scenarios lack experimental support, leading to gaps in the results. Those gaps can be filled with the Fuzzy Logic Method, which evaluates with "degrees of truth" instead of "true or false". With this study, the level of knowledge on providing thermal comfort can be increased by filling the gaps in the empirical studies and the damage caused by heating-cooling energy to the environment can be reduced with further studies.

Keywords: *Architectural comfort parameters, thermal comfort assessment, Fuzzy Logic, PMV.*

Ampirik Termal Konfor Değerlendirme Yöntemlerinin Bulanık Mantıkla Zenginleştirilmesi

Öz

Yapı kullanıcıları zamanlarının yaklaşık %90'ını iç hava kalitesi, görsel konfor, akustik konfor ve ısıl konfor (diğerlerine göre daha baskın olmak üzere) aradıkları iç mekanlarda geçirmektedirler. Isıl konfor; hava sıcaklığı, hava hızı ve bağıl nem gibi fiziksel parametreler üzerinden incelenmekte ve insanların aktivite seviyesi ve giyim seviyesi de ısıl konforun düzeyinde etkili olmaktadır. ISOEN7730 ve EN15251 gibi ilgili yönetmelikler ve standartlar, konunun profesyonellerce benzer şekilde anlaşılmasını sağlamayı amaçlamaktadır. Bu çalışmalar deneysel yöntemlere dayandığından, bir deneyle desteklenmeyen durumlar için literatürde yer alan sonuçlarda boşluklar vardır. Bu boşluklar "doğru-yanlış" yerine "doğruluk dereceleri" ile değerlendirme yapan Bulanık Mantık Yöntemi ile doldurulabilmektedir. Bu çalışma ile ampirik çalışmalarda yer alan sonuçlardaki boşluklar doldurularak ısıl konforun sağlanması konusundaki bilgi düzeyi artırılabilir ve ileriki çalışmalarla ısıtma-soğutma için harcanan enerjinin çevreye verdiği zarar azaltılabilir.

Anahtar kelimeler: *Mimari konfor parametreleri, ısıl konfor değerlendirmesi, bulanık mantık, PMV.*

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1. Introduction

Energy consumption, which is the main source of global warming-based concerns, has been the subject of many studies, especially in the last half of this century. Buildings constitute 40% of the said global energy consumption and providing the optimum thermal well-being in buildings is a large part of this (Costa, Keane, Torrens & Corry, 2013; Yang, Yan & Lam, 2014). With the increase in building stock brought by globalization and modernization, the common use of mechanical methods in building cooling/heating systems, it is possible to provide thermal comfort in buildings by artificial means such as HVAC systems (Taleghani, Tenpierik, Kurvers & Van Den Dobbelsteen, 2013). The use of HVAC systems corresponds to nearly 50% of the energy consumption in non-residential buildings (D'Ambrosio Alfano, Olesen, Palella & Riccio, 2014; Wong & Khoo, 2003). According to Taleghani et al. (2013) thermal comfort in buildings has been discussed since 1930s and is one of the increasingly popular issues to be addressed in the building design phase, as it is directly related to people's health, well-being, as well as the energy performance and efficiency of a building (D'Ambrosio Alfano et al., 2014; Taleghani et al., 2013).

1.1. Thermal Comfort

Thermal comfort can be defined as a person's satisfaction with the thermal environment around him/her and is examined over physical elements such as operative air temperature, relative humidity and air velocity. Apart from these, people's activity and clothing level are also effective. The related studies, regulations, and standards (Figure 1) like ISO EN 7730 and EN 15251 aim to provide a similar sense of the matter (Olesen & Parsons, 2002).

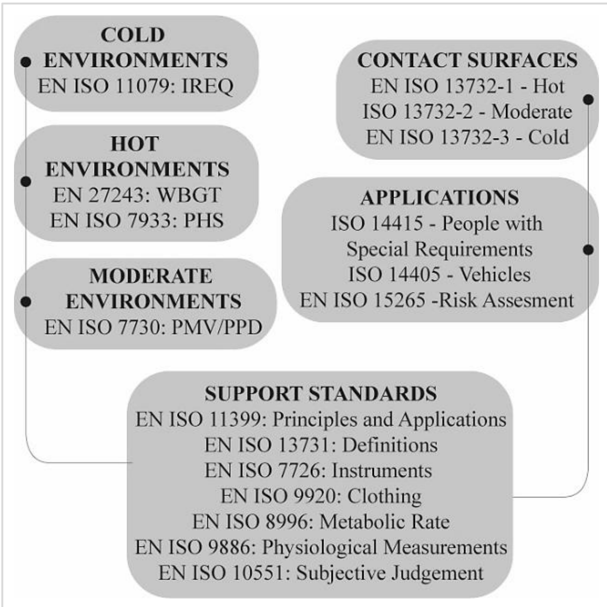

Figure 1. The main CEN and ISO standards regarding thermal comfort (D'Ambrosio Alfano et al., 2014)

The issue of thermal comfort is important for three reasons in particular (Nicol, 1993; Taleghani et al., 2013):

- to provide a satisfying thermal environment for building occupants,
- to control excess energy consumption while doing so (Omer, 2008; Sayigh & Marafia, 1998) and
- to set standards and create common sense.

Additionally, according to Raw & Oseland (1994), the benefits of improving knowledge about thermal comfort can be exemplified as: achieving improved indoor-air quality (Chen & Chang, 2012; Khodakarami & Nasrollahi, 2012; Ormandy & Ezratty, 2012) and energy savings, controlling environmental conditions indoors, reducing CO_2 emissions and the harm on the environment, increasing the work efficiency of building occupants (Kottek, Grieser, Beck, Rudolf & Rubel, 2006) and improving and developing standards while doing so (Raw & Oseland, 1994). Moreover, many studies on indoor comfort conditions have shown that thermal comfort is the most effective on building occupants compared to other comfort parameters which are indoor air quality, visual comfort, and acoustic comfort (Frontczak & Wargocki, 2011).

Thermal comfort can be evaluated by two different methods (Taleghani et al., 2013):

• Climate-chamber studies which take place in chambers where different climatic environments can be created while personal variables like the metabolic rate and the clothing insulation can be determined and varying parameters such as air temperature, humidity and air velocity can be controlled.

• Field studies which yield real-world results obtained by observing an indoor space without interfering with any of the environmental data while recording the clothing insulation and the metabolic rate values of the test subjects.

While both climate and personal variables can be intervened in experiments performed in climate-chambers, in field studies only controlled changes in personal variables can be made. Accordingly, climate-chamber studies can be used for a more specific condition anywhere in the world, while field studies can reflect more realistic conditions. However, the data obtained from climate-chamber studies or field studies are carried out under certain conditions or measured data in specific occasions. Perceiving these data as universal values can also lead to confusion about thermal comfort evaluation and is compounded by the fact that only a few of the many parameters included in the standards are considered during the building application process (D'Ambrosio Alfano et al., 2014). Some gaps may arise in the literature in applying these results to real life as they were obtained in these standards, which were created under certain specific conditions.

1.2. Aristotelian Logic

According to Aristotelian Logic (also referred to as classical or traditional logic and is a formal logic system that originated from the ancient Greek philosopher Aristotle), a proposition is either completely true or completely false; there is no gray area. It is regarded as one of the earliest and most influential logic systems in Western philosophy and has had a considerable influence on the evolution of logic and philosophy throughout history. Aristotelian logic is grounded in a core set of elementary principles and concepts, comprising (Groarke, n.d.):

i. The Law of Non-Contradiction dictates that contradictory statements cannot simultaneously be true in the same manner at the same moment. Therefore, if a statement is true, its negation must be false.

ii. The Law of Excluded Middle dictates that any statement is either true or false, with no middle or third option. It is commonly stated as "either A is true, or not-A is true."

iii. Categorical Propositions: Aristotle's logic mainly pertains to categorical propositions, which state a connection between two categories or classes of objects. These propositions can be categorized into four fundamental forms, each having a specific structure:
   - All S is P (Universal Affirmative)
   - No S is P (Universal Negative)
   - Some S is P (Particular Affirmative)
   - Some S is not P (Particular Negative)

iv. Syllogisms: Aristotle's logic is renowned for its emphasis on syllogisms, which constitute deductive reasoning comprising of three propositions: two premises and a conclusion. Syllogisms follow a logical structure, where the conclusion must be true if the premises are true. An instance of a syllogism in Aristotelian logic is the following:
   - All humans are mortal (major premise)
   - Socrates is a human (minor premise)
   - Hence Socrates is mortal (conclusion)

However, in real life, reconcilable values are needed when there are no parameters to fully meet the right or wrong in some situations. While the results of the experiments mentioned above are valid only in certain mathematically expressed conditions, Fuzzy Logic can be used to answer the question of what will happen in another situation that is very close but slightly different.

1.3. Fuzzy Logic

The term Fuzzy Logic has started to be discussed with the proposal of Fuzzy Set Theory introduced by Iranian-Azerbaijani mathematician Lotfi Zadeh in 1965. Fuzzy sets are mathematical tools that represent uncertainties and indefinite information. With these models, imprecise information and data can be represented, designed, recognized, interpreted, and used. Fuzzy Logic method can be used where different cases can take truth values - any real number between 0 and 1. The aim with Fuzzy Logic is to evaluate partial truth in the field where the truth value can vary from completely true to completely false whereas according to Boolean/Aristotelian Logic, the truth values of the variables can only be 0 or 1. This allows Fuzzy Logic to be used in solutions to be produced for all situations encountered in life that cannot be explained by absolute truth or absolute false (Cintula, Fermüller & Noguera, 2016; Wesley Chai, 2021).

Using Fuzzy Logic can sometimes be the only solution method for problems that require being able to draw conclusions consistent with imprecise, relative, or verbal information (Pakdamar & Güler, 2012). Fuzzy Logic is used in areas such as the construction and operation of technological devices, transportation, company operation, agriculture, health, artificial intelligence modeling, as well as almost every engineering/architectural subject and technological studies (Ödük, 2019). Studies carried out with the Fuzzy Logic method in the field of architecture vary and are used for problem solving in many technical problems of architectural design, structural engineering and building physics.

Baran Ergül, Varol Malkoçoğlu & Acun Özgünler (2022) compared the advantages and disadvantages of traditional design methods and decision support methods using information and communication technologies including fuzzy logic. Examining the studies in which fuzzy logic was used, they classified the concept of design under the headings of conceptual, structural, building element design, space design, product development, material selection and project management. Pakdamar & Tuğrul Okbaz (2018) used Fuzzy Logic Method as a decision-making method in high-rise buildings considering the amount of land, land unit price, registered building density and population density in the environment as inputs. Çekmiş (2016) used Fuzzy Logic as a decision-making method on an architectural site plan design and to find the optimum settlement using distance from the beach and market, the neighborhood, and the view as input parameters. Another study on building physics evaluated indoor air quality, thermal comfort and visual comfort in buildings with Fuzzy Logic method and use MATLAB/Simulink to present the data (Kolokotsa, Tsiavos, Stavrakakis, Kalaitzakis & Antonidakis, 2001). Kolokotsa (2007) also focused on applications concerned with regulating and modelling indoor thermal comfort, visual comfort, indoor air quality and examined the studies on this subject using the Fuzzy Logic method. In the studies examined, it has been observed that energy savings can be achieved when using the HVAC system, thanks to the provision of thermal comfort with the fuzzy logic method (Kolokotsa, 2007).

In this context, it is decided to use the Fuzzy Logic method has been implemented in this paper to evaluate the thermal comfort conditions and to fill the existing gaps in the literature that were not included in the experimental studies.

1.4. The Aim and Scope of the Study

The aim of the study is to generate a Fuzzy Logic-based model to complete the gap in the data set formed by the empirical information obtained from numerous climate-chamber studies and standards on thermal comfort. The mathematical-based Fuzzy Logic system, which was obtained with a limited amount of data for this article, can be further developed with more data in future studies. Although this study was expressed on providing thermal comfort, it also represents a method that can be used for other comfort parameters such as indoor air quality, visual comfort, and acoustic comfort. The generated Fuzzy Logic model of thermal comfort is limited to 6 inputs and 26 membership functions of these inputs. Although this situation varies according to the number of comfort parameters and the available data, the model will work effectively even if the number of the inputs are increased or decreased.

The material and the methodology of the study will be given respectively in Section 2. Following these, in Section 3, the Fuzzy Logic model will be explained and the Fuzzy Logic Model ΔPMV results and a comparative discussion with current literature will be presented. If finally in Section 4, the conclusions and recommendations regarding this article will be given.

2. Materials and Methods

In this article, the information in the standards and regulations related to thermal comfort assessment based on experimental methods has been enriched by using the Fuzzy Logic model and it is aimed to increase the level of knowledge on the subject. In this section, the thermal comfort evaluation system and the Fuzzy Logic methodology used in the study are explained respectively.

2.1. Thermal Comfort Evaluation

Thermal comfort can be evaluated with two main models: climate chamber studies and field studies. Climate chamber studies consist of information obtained from a series of experiments carried out under certain conditions in climate chambers, whereas field studies usually consist of information from real-life measurements (D'Ambrosio Alfano et al., 2014). Detailed analysis of thermal comfort evaluation methods and their comparison can be accessed in references (Brager & de Dear, 1998; Djongyang, Tchinda & Njomo, 2010; Taleghani et al., 2013) Whether a particular thermal condition is acceptable to a large group of people can be estimated by the PMV (predicted mean vote) index Metin girmek için buraya tıklayın veya dokunun.(Yang et al., 2014).

PMV has been formulated based on numerous tests on people under specific conditions by ISO 7730 standard in thermally controlled climate chambers. It is affected by parameters such as air temperature, humidity, air velocity, clothing insulation, activity level and works with an ASHRAE 7-points sensation scale (Olesen & Parsons, 2002) (+3.0 for hot sensation, +2.0 for warm sensation, +1.0 for moderately warm sensation, 0.0 for neutral sensation, -1.0 for moderately cool sensation, -2.0 for cool sensation and -3.0 for cold sensation). The parameters have ranges of application such as: air temperature between 10 degrees Celsius to 30 degrees Celsius, air velocity between 0.0 to 1.0 m/s, metabolic rate between 0.8 to 4.0 met (one metabolic equivalent=the amount of oxygen consumed while doing any activity, 1 met = 58,2 W/m2 (Öz, Korcan & Bulduk, 2018)), clothing insulation between 0.0 to 2.0 clo (thermal resistance of clothing, 1 clo equals to 0.155 m^2/W (Öz et al., 2018)) and PMV rates between -3.0 to +3.0 (Olesen, 2012; Yang et al., 2014). People's expectancy level also plays role as in how they perceive the matter according to their psychological evaluation of thermal comfort state in Categories I to IV. When people have a high level of thermal expectation, it is classified as Category I according to EN 15251 and ISO 7730 Standards (Olesen, 2012; Olesen & Parsons, 2002; Yang et al., 2014). That category includes very fragile, sensitive, handicapped, sick or elderly people and young children. Category II covers the cases of new buildings or buildings that are being renovated and means a normal level of thermal expectation. Category III covers the cases for existing buildings and means a mildly acceptable or moderate level of thermal expectation. And lastly Category IV covers the cases that have values outside the other categories and can be valid for a certain time for the year. For this reason, situations that are or may be classified in this category are excluded from the climate chamber studies. According to current studies, PMV value examples for particular operative temperatures are specified in EN 15251 Standard. In Table 1 (Olesen, 2012; Yang et al., 2014) the design value examples for specific thermal comfort parameters can be seen. Type A stands for "Landscaped office building (1.2 met)", Type B stands for "Kindergarten (1.4 met)", Type C stands for "Department store (1.6 met)"; "Icl,dyn is 0.5 clo (summer) and 1.0 clo (winter); categories on people's expectation level (I,II and III) are as described above (IV excluded). V_a stands for air velocity, RH stands for relative humidity, t_0 stands for minimum temperature in summer or winter for the specific climate chamber condition.

Table 1. Design value PMV examples for the operative temperature according to EN 15251 Standard (Olesen, 2012; Olesen & Parsons, 2002; Yang et al., 2014)

Type	Category	$t_{o,min,winter}$(°C)	V_a= 0.05 m/s		V_a= 0.10 m/s		V_a= 0.15 m/s	
			RH=40%	RH=60%	RH=40%	RH=60%	RH=40%	RH=60%
A	I	21.00	-0.20	-0.10	-0.30	-0.20	-0.40	-0.30
	II	20.00	-0.40	-0.30	-0.50	-0.40	-0.60	-0.50
	III	19.00	-0.60	-0.50	-0.80	-0.70	-0.80	-0.70
B	I	19.00	-0.30	-0.30	-0.40	-0.30	-0.50	-0.40
	II	17.50	-0.60	-0.50	-0.70	-0.60	-0.80	-0.70
	III	16.50	-0.80	-0.70	-0.90	-0.80	-1.00	-0.90
C	I	17.50	-0.40	-0.30	-0.40	-0.30	-0.40	-0.40
	II	16.00	-0.60	-0.50	-0.70	-0.60	-0.70	-0.60
	III	15.00	-0.80	-0.70	-0.80	-0.80	-0.90	-0.80
Type	**Class**	$t_{o,min,summer}$(°C)	V_a= 0.05 m/s		V_a= 0.10 m/s		V_a= 0.15 m/s	
			RH=40%	RH=60%	RH=40%	RH=60%	RH=40%	RH=60%
A	I	25.50	0.10	0.30	0.00	0.10	-0.10	0.00
	II	26.00	0.30	0.43	0.20	0.30	0.10	0.20
	III	27.00	0.60	0.70	0.50	0.60	0.40	0.60
B	I	24.50	0.10	0.20	-0.00	0.10	-0.10	0.00
	II	25.50	0.30	0.50	0.30	0.40	0.20	0.30
	III	26.00	0.50	0.60	0.40	0.50	0.30	0.50
C	I	24.00	0.10	0.30	0.10	0.20	0.00	0.10
	II	25.00	0.40	0.50	0.30	0.40	0.30	0.40
	III	26.00	0.60	0.80	0.60	0.70	0.50	0.70

According to Yang et al. (2014) this data can only be valid under the specific test conditions assumed for specific temperature, air velocity, activity level, clothing level and humidity. However, in the real-world, situations other than these specific experimental conditions can also be encountered. In such conditions, analysis methods such as Fuzzy Logic can be useful.

2.2. Fuzzy Logic Method

The Fuzzy Logic working principle can be summarized as follows:

- Firstly, sharply expressed input and output parameters of the problem, which can be verbal, are determined by the Aristotelian Logic.
- Secondly, the fuzzification process -which is the process to define a membership function for the input parameters- is performed.
- Thirdly, the logical relationships between the input parameters and output parameters are determined to form a rule base with IF-THEN statements. The rule base determination process can be verbal or numerical and the form of knowledge can be empirical, observatory, experienced or foresighted. Fuzzy Logic is a flexible system where all these knowledge and data types can be modeled and digitized.
- After the Fuzzy rule base is applied to the model, the Fuzzy inference system becomes available in the Fuzzy Logic operator. Thus, the resulting data obtained is fuzzified. To be understandable in machine language, sharp (Aristotelian) output data is obtained by applying defuzzification process (Pakdamar & Güler, 2012).

Steps followed in this study when creating the Fuzzy Logic model are shown in Figure 2. As seen in the chart, firstly, the available existing information in the literature and standards on the subject was obtained. To produce a model that can measure thermal comfort, six inputs and their membership functions given according to EN 15251 standard (Olesen, 2012; Olesen & Parsons, 2002; Yang et al.,

2014) specified in Table 1 are determined. With If-Then rule sets, ΔPMV values in the literature are defined in the model. With the fuzzification and defuzzification process through the MATLAB program Fuzzy Logic Toolbox application, defuzzification can be done with five built-in methods and a single and clear output can be obtained from Fuzzy sets. These methods are called middle of maximum, smallest of maximum, largest of maximum, bisector, and centroid. In this study, "centroid method" was used as the defuzzification method. Centroid defuzzification considers the center of gravity of the Fuzzy set along the x-axis (The MathWorks Inc., 2023) and results with real numbers obtained as a result of defuzzification. In this wise, enriched ΔPMV values were obtained. These new values could be derived by querying the system of intermediate values that are not found in the existing literature. Detailed information on the generation of the Fuzzy Logic model in the MATLAB program is given in Section 3.

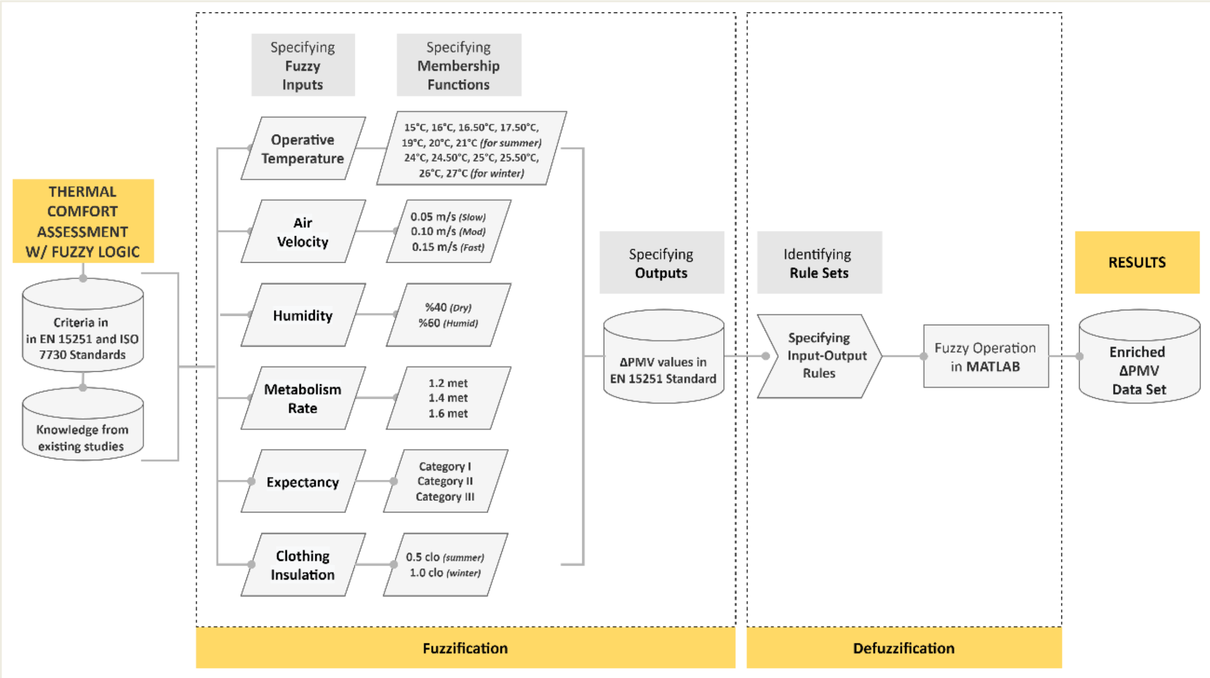

Figure 2. Chart describing the methodology of the study and fuzzification/defuzzification process

3. Results and Discussion

3.1. Creation of the Fuzzy Logic Model

To create the Fuzzy Logic model of thermal comfort in line with the existing information obtained; inputs, membership functions, outputs and relations between them are determined and to express the model visually, the MATLAB (R2022b) program and its Fuzzy Logic Designer plug-in have been used.

6 inputs (operative air temperature, relative humidity, air velocity, metabolism rate, expectancy rate and clothing insulation), 26 membership functions (13 for operative temperature, 3 for air velocity, 2 for humidity, 3 for metabolic rate, 3 for expectancy and 2 for clothing insulation – 26 in total) and 1 output (ΔPMV) are as seen in Table 2.

Table 2. The inputs, membership functions and outputs of the model

Inputs	Membership functions	Output
Operative temperature	15°C, 16°C, 16.50°C, 17.50°C, 19°C, 20°C, 21°C (for winter) 24°C, 24.50°C, 25°C, 25.50°C, 26°C, 27°C (for summer)	ΔPMV design values in EN 15251 Standard
Air velocity	0.05 m/s; 0.10 m/s and 0.15 m/s	
Humidity	40% and 60%	
Metabolism rate	1.2 (A); 1.4 (B); 1.6 (C) met	
Expectancy	Categories I-II and III	
Clothing insulation	0.5 clo (for summer) and 1.0 clo (for winter)	

After the inputs, the rule sets (Table 3), the membership degrees of the inputs (Figure 3) and the membership degrees of the outputs (Figure 4) were determined, and they were entered into the Fuzzy Logic model respectively. Each of these diagrams represent the degree of truth of the input in specific conditions.

Table 3. Example rule sets in the Fuzzy model (6 out of 108 are given) (Olesen, 2012; Olesen & Parsons, 2002; Yang et al., 2014)

Rule Sets
Rule No.1: IF temperature is 21°C and air velocity is 0.05 m/s and metabolism rate is 1.2 met (office) and relative humidity is 40% and expectation level is I (high) and clothing insulation is 1.0 clo THEN ΔPMV is -0.2.
Rule No.2: IF temperature is 20°C and air velocity is 0.05 m/s and metabolism rate is 1.2 met (office) and relative humidity is 40% expectation level is II (med) and clothing insulation is 1.0 clo THEN ΔPMV is -0.4.
Rule No.3: IF temperature is 19°C and air velocity is 0.05 m/s and metabolism rate is 1.2 met (office) and relative humidity is 40% expectation level is III (low) and clothing insulation is 1.0 clo THEN ΔPMV is -0.6.
Rule No.4: IF temperature is 19°C and air velocity is 0.05 m/s and metabolism rate is 1.4 met (kindergarten) and relative humidity is 40% and expectation level is I (high) and clothing insulation is 1.0 clo THEN ΔPMV is -0.3.
Rule No.5: IF temperature is 17.5°C and air velocity is 0.05 m/s and metabolism rate is 1.4 met (kindergarten) and relative humidity is 40% and expectation level is II (med) and clothing insulation is 1.0 clo THEN ΔPMV is -0.6.
Rule No.108: IF temperature is 26°C and air velocity is 0.15 m/s and metabolism rate is 1.6 met (department store) and relative humidity is 60% and expectation level is III (low) and clothing insulation is 0.5 clo THEN ΔPMV is 0.7.

As stated above the operative temperature levels vary between 14-28°C, the air velocity levels are standardized as 0.05 m/s (slow air flow), 0.10 m/s (moderate air flow) and 0.15 m/s (rapid air flow) and relative humidity can differ between 40-60%. The metabolism rate for specific space and activity conditions for this study is limited to three examples as Type A stands for "Landscaped office building (1.2 met)", Type B stands for "Kindergarten (1.4 met)", Type C stands for "Department store (1.6 met)"; "$I_{cl,dyn}$ (dynamic clothing insulation) is 0.5 clo (for summer) and 1.0 clo (for winter); categories on people's expectation level (I,II and III) are as stated earlier. And lastly the clothing insulation level is accepted as 0.5 clo (lightweight clothing) for summer season and 1.0 clo (heavy clothing) for winter season. 108 rule sets were defined in the program and the example rule sentences can be seen in Table 3. In each rule, the inputs and their degrees of memberships are connected by the "and" conjunction and they reach a conclusion value. Thus, the changing input values cause the result values to change.

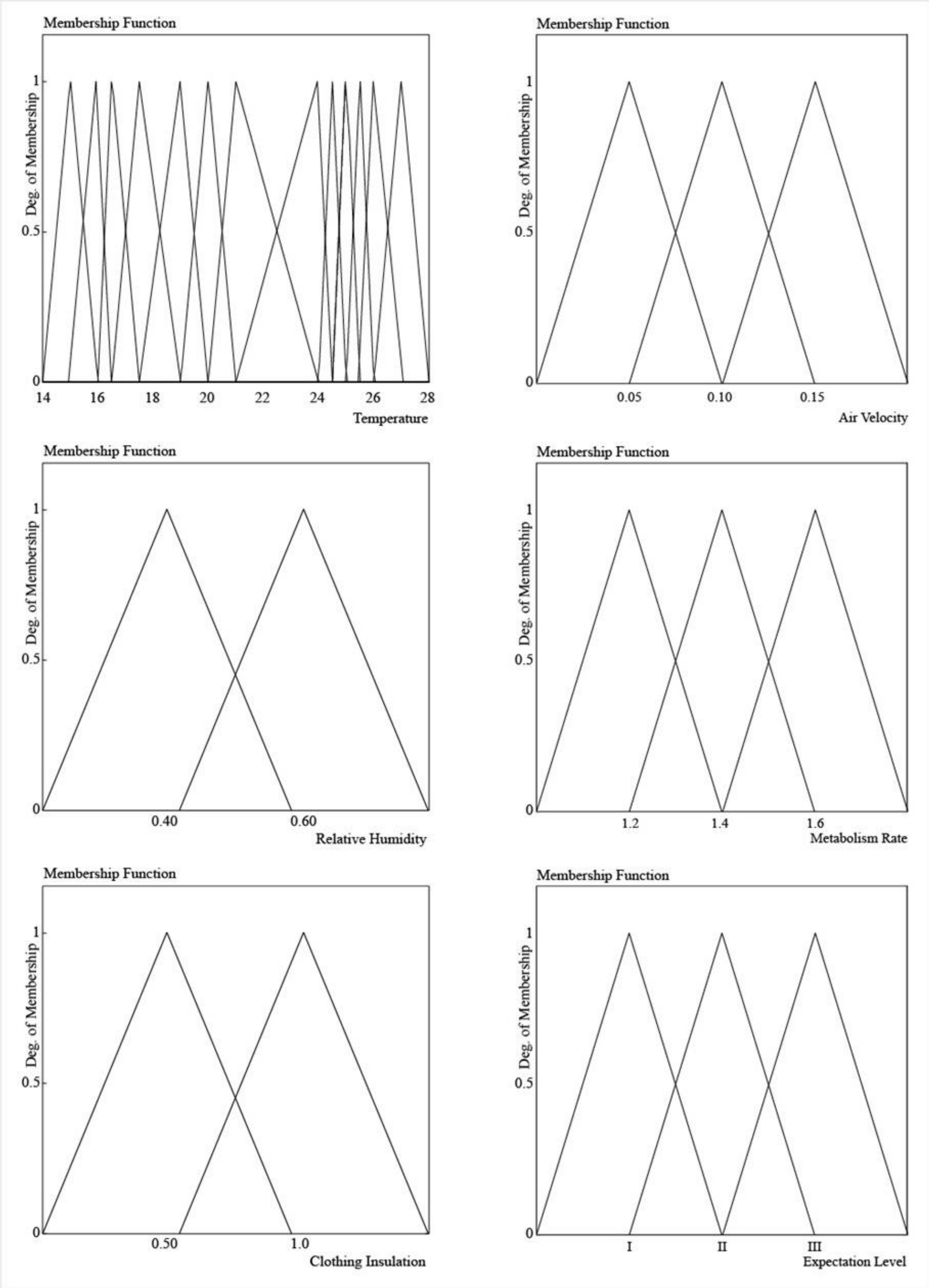

Figure 3. Degree of membership graphics of triangular membership functions of the inputs identified in the MATLAB program (operative air temperature, relative humidity, air velocity, metabolism rate, clothing insulation and expectation level)

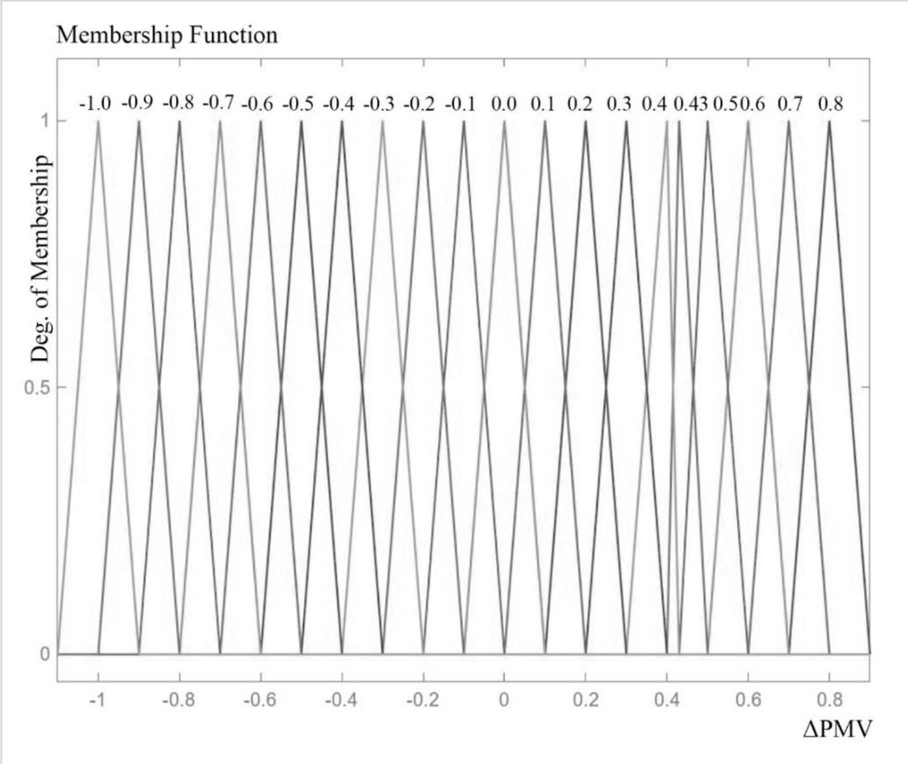

Figure 4. Degree of membership graphic of the outputs identified in the MATLAB program

3.2. Fuzzy Logic Model ΔPMV Results

In this part of the article, the ΔPMV results obtained with the created Fuzzy Logic model are examined. The figures below show the ΔPMV results for six known inputs as an example. In Figure 5, the temperature is 21°C, the metabolism rate is 1.2 met (office), the air velocity is 0.05 m/s, the relative humidity is 40%, expectation level is I (high) and clothing insulation is 1.0 clo. As a result of these input values, the ΔPMV is -0.2 as stated in Rule No.1. In Figure 6, the temperature is 20°C, the relative humidity is 40%, the air velocity is 0.05 m/s, the metabolism rate is 1.2 met (office), the expectation level is II (med) and the clothing insulation is 1.0 clo. As a result of these input values, the ΔPMV is -0.4 as stated in Rule No. 2. In Figure 7, the temperature is 19°C, the relative humidity is 40%, the air velocity is 0.05 m/s, the metabolism rate is 1.2 met (office), the expectation level is III (low) and the clothing insulation is 1.0 clo. As a result of these input values, the ΔPMV is -0.6 as stated in Rule No. 3. In Figure 8, the temperature is 19°C, the relative humidity is 40%, the air velocity is 0.05 m/s, the metabolism rate is 1.4 met (kindergarten), the expectation level is I (high) and the clothing insulation is 1.0 clo. As a result of these input values, the ΔPMV is -0.3 as stated in Rule No. 4 earlier. In Figure 9, the temperature is 17.5°C, the relative humidity is 40%, the air velocity is 0.05 m/s, the metabolism rate is 1.4 met (kindergarten), the expectation level is II (med) and the clothing insulation is 1.0 clo. As a result of these input values, the ΔPMV is -0.6 as stated in Rule No. 5. In Figure 10, the temperature is 26°C, the relative humidity is 60%, the air velocity is 0.15 m/s, the metabolism rate is 1.6 met (department store), the expectation level is III (low) and the clothing insulation is 0.5 clo. As a result of these input values, the ΔPMV is -0.7 as stated in Rule No. 108 earlier. Since all 108 of the rules do not fit in the images, only the rules triggered by the input values are shown in Figures 5-12. As a result of the inputs determined in the rules, the weights of the ΔPMV outputs obtained according to the centroid method (center of gravity of the Fuzzy set along the x-axis) are given in the lower right corner of the figures.

Looking at these examples, it is seen that the model created gives the correct and precise ΔPMV values for certain conditions, as in the standards, over the data entered before. Additionally, and more importantly, the Fuzzy Logic model can also give ΔPMV values for conditions that are not strictly defined (as mentioned in the examples above). In Figure 11, one of the inputs of Rule No. 1 – the air velocity is changed from 0.05 to 0.08 – the Fuzzy Logic model can still give an answer about ΔPMV as -0.258. Or in Figure 12, three of the inputs of Rule No. 1 – the air velocity is changed from 0.05 to 0.09, the relative humidity is changed from 40% to 45% and the metabolism rate is changed from 1.2 to 1.3; the Fuzzy Logic model gives the ΔPMV value as -0.231. In this wise, the Fuzzy Logic model can produce new results for values between the existing data, and thus the model can better respond to situations encountered in real life.

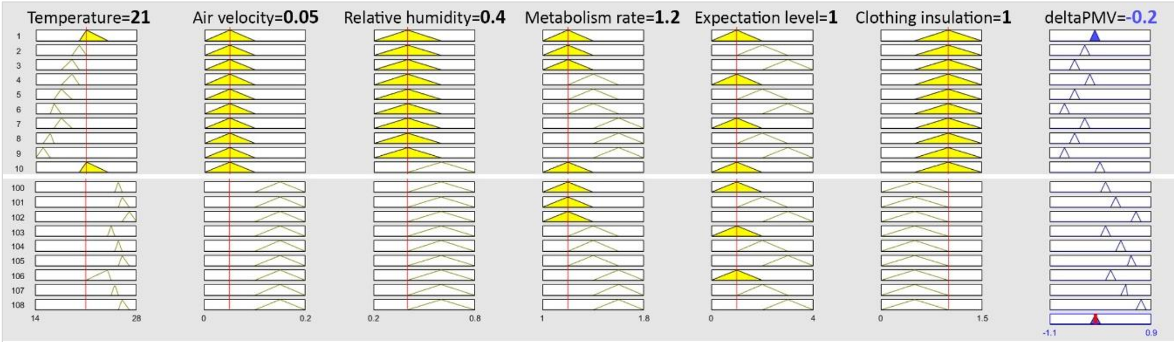

Figure 5. Rule Inference and the ΔPMV output for Rule No. 1 (ΔPMV = -0.2)

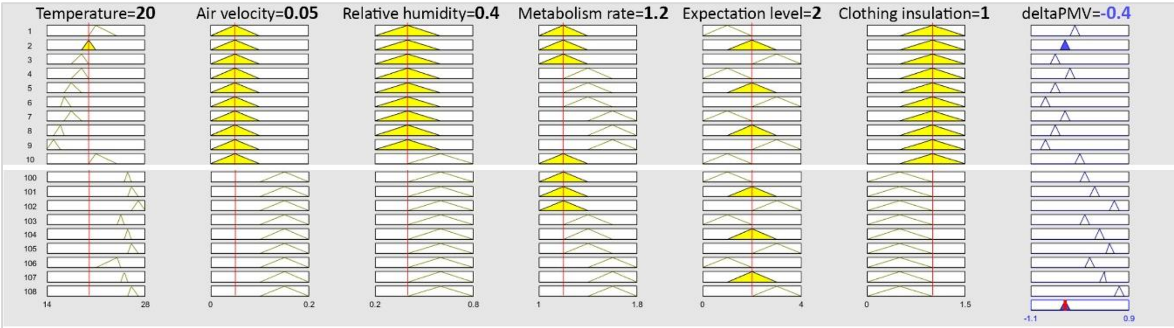

Figure 6. Rule Inference and the ΔPMV output for Rule No. 2 (ΔPMV = -0.4)

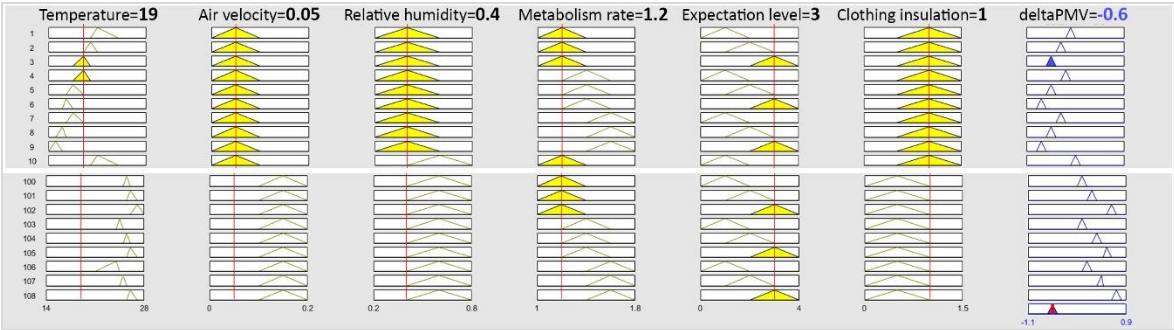

Figure 7. Rule Inference and the ΔPMV output for Rule No. 3 (ΔPMV = -0.6)

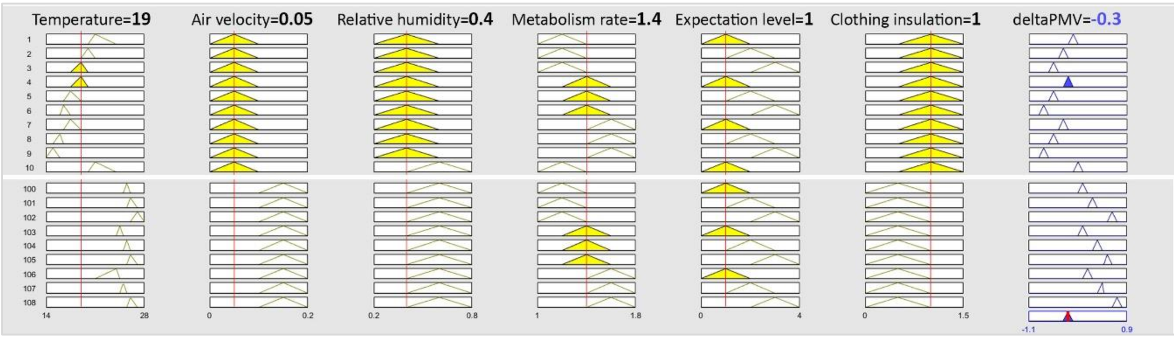

Figure 8. Rule Inference and the ΔPMV output for Rule No. 4 (ΔPMV =-0.3)

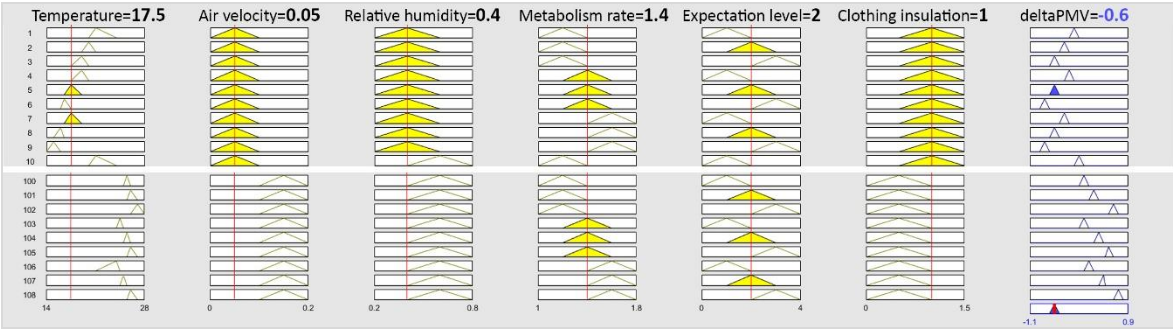

Figure 9. Rule Inference and the ΔPMV output for Rule No. 5 (ΔPMV =-0.6)

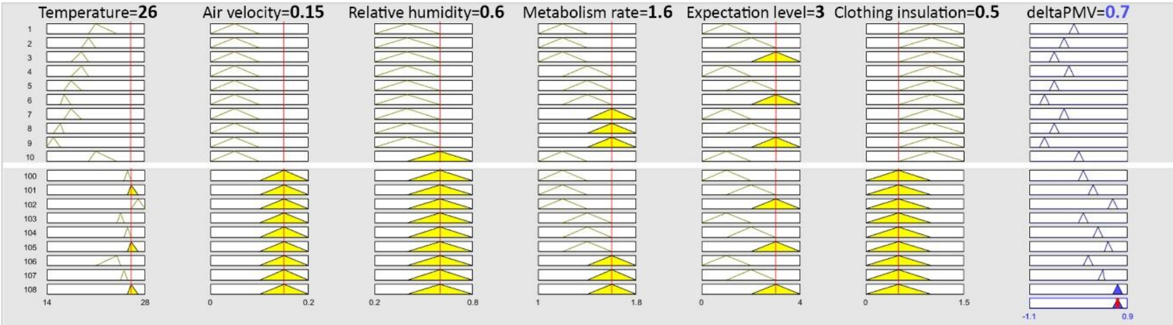

Figure 10. Rule Inference and the ΔPMV output for Rule No. 108 (ΔPMV =-0.7)

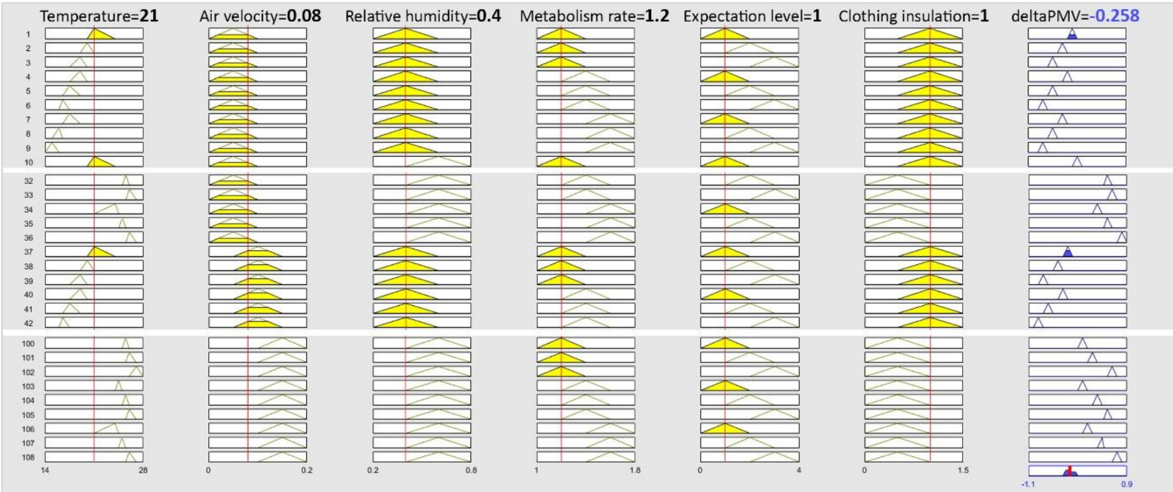

Figure 11. Rule Inference and the ΔPMV output by changing the air velocity value of Rule No. 1 (ΔPMV =-0.258)

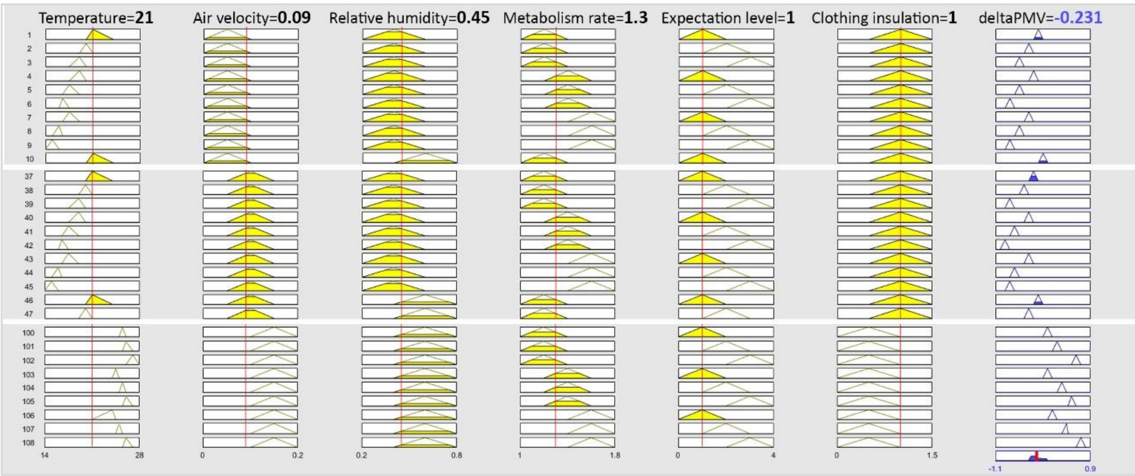

Figure 12. Rule Inference and the ΔPMV output by changing the air velocity, relative humidity and metabolism rate values of Rule No. 1 (ΔPMV = -0.231)

3.3. Comparison of the Findings with the Relevant Literature

In this article, a Fuzzy Logic model was created by using the results obtained from experimental studies as input. The model, which was created with 6 inputs, 26 membership functions and 108 rules, and yielded successful results for reconcilable values as well. The studies examined in the literature vary in terms of the number and quality of inputs they use. From this, the performance and capacity of the produced model are also affected.

While Pakdamar & Tuğrul Okbaz (2018) created the model with 4 verbal inputs (the amount of land, land unit price, registered building density and population density in the environment) and 16 rules, Çekmiş (2016) implemented Fuzzy Logic with 3 verbal inputs (distance from the beach and market, the neighborhood, and the view) and 36 rules. In both studies, the membership functions of the inputs were determined intuitively as "less-moderate-many" and it was stated that the number of inputs could be increased in future studies and the precision of the findings may be enhanced (Çekmiş, 2016; Pakdamar & Tuğrul Okbaz, 2018).

Furthermore, Baran Ergül et al. stated that creating models using Fuzzy Logic may result in time-consuming processes due to the use of a trial-and-error method for determining membership function selections (Baran Ergül et al., 2022).

Accordingly, in this article, it is thought that the fact that the inputs are based on an objective and experimental basis and that the number of inputs is enough and many, causes the accuracy of the results to increase comparing to the studies mentioned above. In addition, since the membership functions of the inputs were determined experimentally, the model could be produced quickly and not by trial-and-error method. It is thought that the study conducted in this article differs positively from the others with these aspects.

4. Conclusion and Recommendations

In today's world, building occupants spend a large part of their life indoors where they seek comfort and numerous studies have shown that people care most about thermal comfort when it comes to indoor comfort conditions. Thermal comfort can be defined as the satisfaction with the thermal environment around a person and is examined over physical parameters such as operative air temperature, relative humidity and air velocity. Apart from these, people's activity and clothing level are also effective. The related studies, regulations, and standards like ISO EN 7730 and EN 15251 aim to provide a similar understanding of the matter.

Since these studies are based on experimental methods which can cover limited cases, there are gaps in the results for cases not supported by an experiment. The gaps mentioned in the literature can be filled with the Fuzzy Logic Method, which is a method that evaluates with "degrees of truth (between 0 to 1)" instead of "true or false (1 or 0)".

Filling the literature gaps in empirical studies and expanding the level of knowledge on thermal comfort by fuzzification method are the main goals of this study. Based on this article, optimum thermal conditions can be more easily achieved for different conditions, less energy compared to today can be used to provide thermal comfort with artificial systems in buildings (like HVAC) and negative effects on the environment can be reduced with future studies.

Firstly, to generate the Fuzzy Logic Model of the thermal comfort, parameters (inputs) affecting thermal comfort; sub-functions (membership functions) and obtained results (outputs) of these parameters were determined. Then, using the MATLAB program and Fuzzy Logic Designer plug-in, pre-existing data was identified into the program and after the fuzzification and defuzzification processes the thermal comfort model was simulated.

As a result of applying the Fuzzy Logic Method, it has been seen that the program can both correctly detect the data entered into the system and reach the result and successfully complete the missing data with its own processing system. The rules below were verified by querying the same values in the system and the ΔPMV values emerged as the same:

- The Rule No. 1 (Figure 5), “IF temperature is 21°C and air velocity is 0.05 m/s and metabolism rate is 1.2 met (office) and relative humidity is 40% and expectation level is I (high) and clothing insulation is 1.0 clo THEN ΔPMV is -0.2.”
- The Rule No. 2 (Figure 6), “IF temperature is 20°C and air velocity is 0.05 m/s and metabolism rate is 1.2 met (office) and relative humidity is 40% expectation level is II (med) and clothing insulation is 1.0 clo THEN ΔPMV is -0.4.”
- The Rule No. 3 (Figure 7) “IF temperature is 19°C and air velocity is 0.05 m/s and metabolism rate is 1.2 met (office) and relative humidity is 40% expectation level is III (low) and clothing insulation is 1.0 clo THEN ΔPMV is -0.6.”
- The Rule No. 4 (Figure 8) “IF temperature is 19°C and air velocity is 0.05 m/s and metabolism rate is 1.4 met (kindergarten) and relative humidity is 40% and expectation level is I (high) and clothing insulation is 1.0 clo THEN ΔPMV is -0.3.”
- The Rule No. 5 (Figure 9) “IF temperature is 17.5°C and air velocity is 0.05 m/s and metabolism rate is 1.4 met (kindergarten) and relative humidity is 40% and expectation level is II (med) and clothing insulation is 1.0 clo THEN ΔPMV is -0.6.”
- The Rule No. 108 (Figure 10) “IF temperature is 26°C and air velocity is 0.15 m/s and metabolism rate is 1.6 met (department store) and relative humidity is 60% and expectation level is III (low) and clothing insulation is 0.5 clo THEN ΔPMV is 0.7.”
- Afterwards, by changing the air velocity value of Rule No.1 from 0.05 to 0.08, the Fuzzy Logic model can give the output ΔPMV as -0.258 (Figure 11).
- Also in another example, by changing the air velocity, relative humidity and metabolism rate values of Rule No.1 – the air velocity is changed from 0.05 to 0.09, the relative humidity is changed from 40% to 45% and the metabolism rate is changed from 1.2 to 1.3; the Fuzzy Logic model gave the ΔPMV value as -0.231 (Figure 12).

By employing this approach, the generated Fuzzy Logic model was able to give results for diverse conditions related to thermal comfort that were not previously covered in the existing literature, which relied on experimental studies. These changes made in the rules can be very diversified within the scope of 6 inputs and 26 membership functions for 108 rules. Consequently, the potential to obtain an expanded number of results can be obtained according to specific requirements or topics.

As mentioned before, the Fuzzy Logic method has been experienced in different areas of architecture and has been used to increase the level of knowledge previously obtained in different design/application issues. It is thought that this study also makes a unique contribution by providing benefit in increasing the level of knowledge about thermal comfort in architectural structures for intermediate values that do not have experimental output data.

In this way, it has been demonstrated that the Fuzzy Logic method can be used in architectural applications to process information and expand the data network. It is hoped that this method will be a useful model for similar architectural issues in future studies.

Acknowledgements and Information Note

The article complies with national and international research and publication ethics. Ethics Committee approval was not required for the study.

Author Contribution and Conflict of Interest Declaration Information

All authors contributed equally to the article. There is no conflict of interest.

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