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FLC-Based Indoor Air Quality Assessment for ASHRAE Standard Conformance

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ABSTRACT

Designed and presented in this paper is Indoor Air Quality Assessment using fuzzy logic technology. Triangular membership functions for classified Air and Gaseous parametric categories are to be constructed in Matlab Fuzzy Logic Toolbox using ASHRAE, EPA and WHO standards. Air parameters include Temperature (T) and Relative Humidity (RH) while Gaseous parameters include Carbon Monoxide (CO) and Carbon Dioxide (CO_2). The parameters are to be classified as Very Good (VG), Good (G), Fair (F), Poor (P) and Very Poor (VP). The Sugeno-style of inference systems is utilized in this proposed to describe the fuzziness of assessing indoor air quality. There were 131 fuzzy rules formulated. The output parameter is classified as Highly Acceptable (HA), Acceptable (A), Just Acceptable (JA), Not Acceptable (NA), and Highly Not Acceptable (HNA). The fuzzy-based system is simulated and the results were further verified using the weighted means of 90 generated data samples.

KEYWORDS: indoor air quality; fuzzy logic; ASHRAE; Matlab toolbox

1 INTRODUCTION

According to (Chih-Hung et al., 2014), in day time, most of us stay indoors for about 80% to 90%. Americans spend 90% of their time indoors according to Centers for Disease Control and Prevention (CDC) [2]. On the average, office workers stayed 40 hours per week in office buildings according to OSHA 3430-04 in 2011. Considering that we stayed indoors most of the time, we should be health conscious and it is a must for all of us to consider long-term health. Thus, research on indoor air quality assessment is deemed important and must be given emphasis. Indoor Air Quality (IAQ) must be assessed, as it affects the quality and efficiency of man's work. Experts believed as well that more people suffer from the effects of indoor air pollution than from the effects of outdoor air pollution. According to U.S. Department of Labor, a major concern to business, school, building and worker is IAQ, as it impacts the health, comfort, well-being, and productivity of the building occupants. Occupational Safety and Health Administration (OSHA) recognizes the need of addressing poor IAQ concerns. Because of energy conservation measures provided for buildings, health effects related to IAQ have increased. The use of Heating, Ventilation, and Air Conditioning (HVAC) (HVAC) systems had increased indoor pollutants concentrations (Wei Cai et al., 2010). Because of this, many research enthusiasts paid attention to IAQ studies. In different countries, indoor environment studies were conducted, which focuses on office or residential buildings (Wei Cai et al., 2010). A new trend in modern architecture is intelligent building.

Key features of this intelligent building include intelligent systems and environmental monitoring. One of the most important factors, which influence the performance of intelligent building, is environmental monitoring (Wang-Kun Chen, 2013). The most critical and difficult part in intelligent systems for controlling indoor environment lie not only on environmental standards, but primarily in the feelings and perceptions of people. Therefore, IAQ must consider the uncertainty and ambiguity derived from individual preferences (Wang-Kun Chen, 2013).
For a fact, Proportional Integral Derivatives (PIDs) could provide reasonable solutions for this research proposed. However, the use of PIDs could bring inconvenience in controlling the uncertainty of the dynamics of HVAC systems. This could be characterized easily using linguistic fuzzy rules. Fuzzy Logic Controllers (FLCs) appear as a viable alternative solution to traditional controllers, since it do not require mathematical model and FLCs are prepared to handle different criteria for dynamics of HVAC system according to the knowledge of a human expert (Solana, 2013). In this study, the proponent will use the concepts and principles of fuzzy logic in the simulation of identified air and gaseous parameters for the assessment of indoor air quality. The factors to be considered for classifying indoor air quality include the temperature and relative humidity for air parameters, and carbon monoxide and carbon dioxide for gaseous parameters respectively. The parameters will be categorized as Very Good, Good, Fair, Poor and Very Poor. The indoor air quality is being classified on the basis of its acceptation. Specifically, the output can be classified as Highly Acceptable, Acceptable, Just Acceptable, Not Acceptable, and Highly Not Acceptable. The proponent preferred to use the Sugeno-style of fuzzy inference system. In this study, the simplest type of membership function, which is the triangular membership function, will be used for its input and output parameter constructions. The proponent would verify the results using Matlab Fuzzy Logic Toolbox. This study will be simulated purely mathematical. This study excludes the use of sensors for data log, feedback and control mechanism, quality control and information management.

2 METHODOLOGY

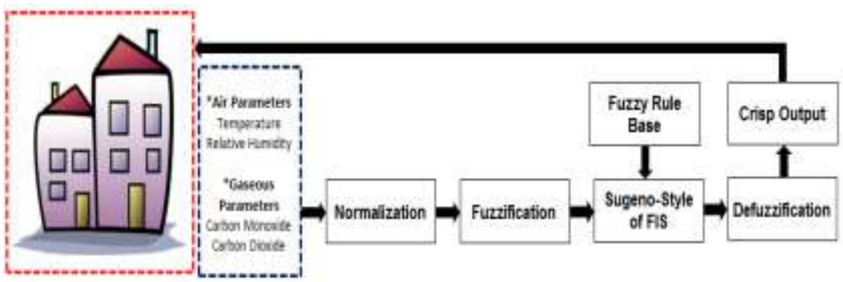

Figure 2.1: Configuration of FLC-based indoor air quality assessment

As shown in **Figure 2.1**, air and gaseous input parameters are sampled and normalized. The normalized data inputs are to be fuzzified by the predefined input fuzzy sets. The fuzzified data will be triggered by the formulated fuzzy rule table. Finally, the inferred data will be defuzzified to give crisp outputs of 1-Highly Not Acceptable, 2-Not Acceptable, 3-Jut Acceptable, 4-Acceptable and 5-Highly Acceptable. This assesses the IAQ, which later on can be improved in meeting IAQ standards and regulations. In this research, the proponent makes use of experimental study. In order for the proponent to effectively construct the membership function for input and output parameters, different standards and guidelines were used. The tolerance and specification limits set and maintained by ASHRAE, Environmental Protection Agency (EPA) and World Health Organization (WHO) were used for this process. Based on these international standards, the proponent identified the minimum and maximum possible range. The proponent generated 90 data for air and gaseous parameters using Excel VBA macro program. The specification limits and the generated data were used for categorizing the input parameters into "very

good", "good", "fair", "poor" and "very poor". The membership functions for temperature, relative humidity, carbon monoxide and carbon dioxide were then constructed. Since the proponent makes use of Sugeno style of fuzzy inference system, it will only need him to set constants for linguistic class. The output parameter constants used are: **1** for Highly Not Acceptable (HNA), **2** for Not Acceptable (NA), **3** for Just Acceptable (JA), **4** for Acceptable (A), and **5** for Highly Acceptable (HA). The challenging part of fuzzy logic is forming its fuzzy rule. In building Fuzzy Associative Memory (FAM) matrix, perception of qualified experts about the linguistic description of indoor air quality was obtained. Also, the proponent had used the tolerance limits set by international standards. For simplicity of the ruling, the proponent assumed that all parameters are equal in terms of criticality. The method used for such data qualification and treatment is averaging technique and trial and error method. The proponent will make use of Matlab Fuzzy Logic Toolbox for simulation purposes.
The hierarchical structure for indoor air quality assessment includes two major blocks. First two blocks will be classified as very good, good, fair, poor and very poor. The last hierarchical level (indoor air quality assessment) classifies the indoor air quality as highly not acceptable, not acceptable, just acceptable, acceptable and highly acceptable. Listed below are sample rules used in this proposed for different hierarchical levels of structure: If *Temperature* is <very good> and *Relative Humidity* is <very good>; **Level 1:** *Then air parameters block is classified as* **<very good>** If *Carbon Monoxide* is <very good> and *Carbon Dioxide* is <very good>; **Level 2:** *Then gaseous parameters block is classified as* **<very good>** If *Air Parameters block* is <very good> and *Gaseous Parameters block* is <very good>; **Level 3:** Then the last hierarchical level for Indoor Air Quality Assessment is classified as **< Highly Acceptable HA>**.

3 MEMBERSHIP FUNCTION CONSTRUCTION

In constructing the membership functions for the identified critical input parameters, the proponent makes use of the definition and description of air and gaseous quality parameter specifications used and adopted by AHSRAE stipulated in Indoor Air Quality Handbook (TSI Incorporated, 2013). Considering that OSHA does not have a general IAQ standard, as it provides only guidelines in addressing the most common workplace complaints about IAQ, the proponent preferred to use other notable standards. In this study, the proponent will make use of ASHRAE standard specifically the addendum to Thermal Environmental Conditions for Human Occupancy (stipulated in the Indoor Air Quality handbook standards and guidelines), EPA and WHO. Specifically, ASHRAE Standard 55-2010 and ISO 7730 will be used for T and RH parameters. ASHRAE Standard 62.1-2010 will be used for CO_2. On the other hand, for CO, EPA, ASHRAE and WHO standards will be used for 8 hr. TWA measure. By these standards, the proponent will build its FAM matrix and it will be verified using the generated 90 samples. These data samples will be clustered into three (3) shifts, as the proponent considers three measures. These measurements include data collection for shift A (6:00am to 2:00pm), shift B (2:00pm to 10:00pm) and shift C (10:00pm to 6:00am). The proponent will compute for the weighted mean of three shifts on a daily basis. For simulation purposes, the computed 30 weighted means will be plugged into the fuzzy system. In giving finer results, the proponent will use trial and error method.

4 DESIGN CONSIDERATIONS

The indoor air quality system requires four (4) inputs from the user/operator. Air parameters include Temperature, which is measured in **˚C** and Relative Humidity in terms of **%**. Gaseous parameters block comprised of Carbon Monoxide and Carbon Dioxide. Both parameters are measured in **ppm** unit. Considering that these parameters have different range of values, the inputs of the user will have to be normalized in fitting to its fuzzy scale of **0 to 1**. The normalized inputs will be fuzzified. Using FAM matrices, the rules trigger the output and it will be defuzzified using centroid of area for Sugeno style of inference system. The obtained crisp output will be used for linguistic classification in determining the acceptation of indoor air quality.

4.1 Fuzzy Associative Memory (FAM) Matrices for Indoor Air Quality Assessment

The FAM matric for air parameters block requires two inputs and classified into nine linguistic classes: VG - Very Good (8.5 to 9.5), G1 - Good1 (7.5 to 8.5), G2 - Good2 (6.5 to 7.5), F1 – Fair1 (5.5 to 6.5), F2 - Fair2 (4.5 to 5.5), P1 - Poor1 (3.5 to 4.5), P2 - Poor2 (2.5 to 3.5), VP1 - Very Poor1 (1.5 to 2.5) and VP2 - Very Poor2 (0.5 to 1.5). Gaseous parameters block, on the other hand, requires two inputs and classified into five linguistic classes: VG - Very Good (4.5 to 5.5), G - Good (3.5 to 4.5), F - Fair (2.5 to 3.5), P - Poor (1.5 to 2.5) and VP - Very Poor (0.5 to 1.5). Finally, Indoor air quality block requires two inputs and classified into five linguistic classes: HA - Highly Acceptable (4.5 to 5.5), A - Acceptable (3.5 to 4.5), JA - Just Acceptable (2.5 to 3.5), NA - Not Acceptable (1.5 to 2.5) and HNA - Highly Not Acceptable (0.5 to 1.5).

Considering that there were two input values and nine classifications for air parameters and two input values and five classifications for gaseous parameters, a total of **81** fuzzy rules were formulated for air parameters and **25** fuzzy rules were formulated for air parameters. For the final block, input parameters include the classified blocks of air parameters and gaseous parameters. There were two inputs and five classifications, which would give **25** fuzzy rule bases. Combining the three levels of assessment, a total of **131** fuzzy rules were formulated. This rule base formation is more efficient compared to **625** rules, which could be generated when we processed simultaneously the four input parameters and classify them into five distinctions. The linguistic variables were converted into its corresponding numerical values. The defuzzified output is interpreted in linguistic class for indoor air quality assessment.

4.2 FIS of Air Parameters

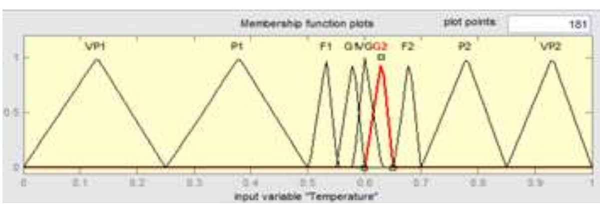

Figure 4.3: Temperature (input)

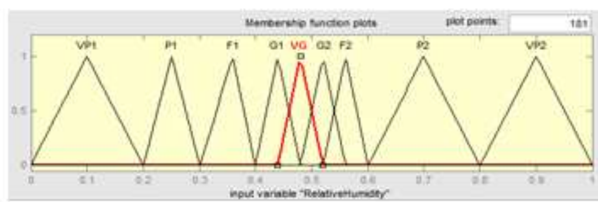

Figure 4.4: Relative Humidity (input)

Based from ASHRAE standard 55-2010 and ISO 7730, we knew that the best temperature at summer is ranging from 23 to 28 ˚C and the best temperature at winter is ranging from 20 to 25.5˚C. Temperature block defined nine membership functions as shown in Figure 4.3.

**(T-VG)*: concentration range of T block is 23 to 25 ˚C. **(T-G)*: concentration range of T block is 22 to 24 ˚C for T-G1 and 24 to 26 ˚C for T-G2. **(T-F)*: concentration range of T block is 20 to 22 ˚C for T-F1 and 26 to 28 ˚C for T-F2. **(T-P)*: concentration range of T block is 10 to 20 ˚C for T-P1 and 28 to 34 ˚C for T-P2. **(T-VP)*: concentration range of T block is 0 to 10 ˚C for T-VP1; 34 to 40 ˚C for T-VP2.

Based from ASHRAE standard 55-2010 and ISO 7730, we knew that the best relative humidity ranges from 30 to 65 %. Relative Humidity block defined nine membership functions as shown in Figure 4.4.

**(RH-VG)*: concentration range of RH block is 44 to 52 %. **(RH-G)*: concentration range of RH block is 40 to 48 % for RH-G1 and 48 to 56 % for RH-G2. **(RH-F)*: concentration range of RH block is 30 to 40 % for RH-F1 and 52 to 60 % for RH-F2. **(RH-P)*: concentration range of RH block is 20 to 30% for RH-P1 and 60 to 80% for RH-P2. **(RH-VP)*: concentration range of RH block is 0 to 20 % for RH-VP1 and 80 to 100 % for RH-VP2.

4.3 FIS of Gaseous Parameters

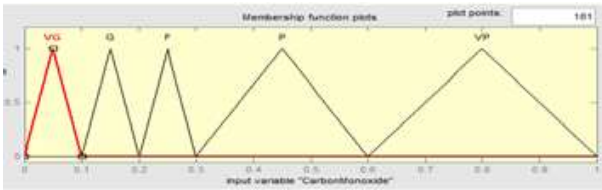

Figure 4.5: Carbon Monoxide (input)

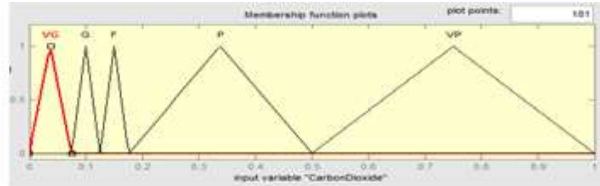

Figure 4.6: Carbon Dioxide (input)

Based from ASHRAE, WHO and EPA standards, we knew that the standard value of concentration of CO is 9 ppm for 8 hr. TWA; therefore any value below 9 ppm is normal and values higher than 9 ppm is considered to be Out-of-Control (OOC) or Out-of-Specifications (OOS). Carbon Monoxide block defined five membership functions as shown in Figure 4.5.

**(CO-VG)*: concentration range of CO block is 0 to 3 ppm. **(CO-G)*: concentration range of CO block is 3 to 6 ppm. **(CO-F)*: concentration range of CO block is 6 to 9 ppm. **(CO-P)*: concentration range of CO block is 9 to 18 ppm. **(CO-VP)*: concentration range of CO block is 18 to 30 ppm.

Based from ASHRAE standard 62.1-2010, we knew that the standard value of the concentration of CO_2 is 700 ppm; therefore any value below 700 ppm is normal and values higher than 700 ppm is considered to be OOC or OOS. Carbon Dioxide block defined five membership functions as shown in Figure 4.6.

**(CO_2-VG)*: concentration range of CO_2 block is 0 to 300 ppm. **(CO_2-G)*: concentration range of CO_2 block is 300 to 500 ppm. **(CO_2-F)*: concentration range of CO_2 block is 500 to 700 ppm. **(CO_2-P)*: concentration range of CO_2 block is 700 to 2000 ppm. **(CO_2-VP)*: concentration range of CO_2 block is 2000 to 4000 ppm.

5 EXPERIMENTS AND ANALYSIS OF RESULTS

In simulating the FLC-based indoor air quality assessment system, the proponent conducted several tests for different values of input ranges on the basis of generated samples. For each parameter, 90 data were generated for tests 1 to 3 using Excel VBA macro program. The proponent computed for the weighted average of the generated data and the crisp outputs for each FIS were obtained as shown in Table 5.1.

Table 5.1 Simulation of FLC-based IAQ assessment based on data generation

Tests	Generated Data Samples				Generated Data Samples (Normalized)				Crisp Output (Matlab Fuzzy Logic Toolbox)			Linguistic Assessment
	Temperature (T)	Relative Humidity (RH)	Carbon Monoxide (CO)	Carbon Dioxide (CO2)	Temperature (T)	Relative Humidity (RH)	Carbon Monoxide (CO)	Carbon Dioxide (CO2)	Air Parameters	Gaseous Parameters	Indoor Air Quality	
1	20.85	56.59	8.14	841	0.52	0.57	0.27	0.21	3	3	3	Just Acceptable
2	34.40	80.80	17.54	1336	0.86	0.81	0.58	0.33	1	2	2	Not Acceptable
3	32.45	54.36	11.69	2350	0.81	0.54	0.39	0.59	2.5	2	3	Just Acceptable
4	24.10	63.83	8.40	1228	0.60	0.64	0.28	0.31	3	3	3	Just Acceptable
5	26.40	38.68	13.89	2582	0.66	0.39	0.46	0.65	3	2	3	Just Acceptable
6	23.64	56.49	11.14	2637	0.59	0.56	0.37	0.66	4	2	3	Just Acceptable
7	18.01	53.06	16.36	2542	0.45	0.53	0.55	0.64	3	2	3	Just Acceptable
8	27.71	48.76	26.00	3213	0.69	0.49	0.87	0.80	3.75	1	3	Just Acceptable
9	11.00	32.50	17.21	2323	0.28	0.33	0.57	0.58	3	2	3	Just Acceptable
10	11.48	54.14	15.59	2560	0.29	0.54	0.52	0.64	3	2	3	Just Acceptable
11	23.16	47.74	27.39	1006	0.58	0.48	0.91	0.25	5	2	4	Acceptable
12	10.40	61.40	16.80	1611	0.26	0.61	0.56	0.40	2	2	2	Not Acceptable
13	16.74	36.84	17.27	2383	0.42	0.37	0.58	0.60	3	2	3	Just Acceptable
14	16.87	50.34	10.36	2394	0.42	0.50	0.35	0.60	3.5	2	3	Just Acceptable
15	15.81	56.50	15.66	2462	0.40	0.56	0.52	0.62	3	2	3	Just Acceptable
16	15.16	66.74	21.69	2037	0.38	0.67	0.72	0.51	2	1	2	Not Acceptable
17	19.43	43.64	10.94	1061	0.49	0.44	0.36	0.27	3	2	3	Just Acceptable
18	13.85	42.14	11.78	2160	0.35	0.42	0.39	0.54	3	2	3	Just Acceptable
19	19.69	36.19	11.60	2094	0.49	0.36	0.39	0.52	3	2	3	Just Acceptable
20	15.76	54.12	11.40	2025	0.39	0.54	0.38	0.51	3	2	3	Just Acceptable
21	17.62	61.40	10.76	1529	0.44	0.61	0.36	0.38	2	2	2	Not Acceptable
22	29.31	46.42	19.09	1926	0.73	0.46	0.64	0.48	3	2	3	Just Acceptable
23	20.40	51.40	16.88	1620	0.51	0.51	0.56	0.40	4	2	3	Just Acceptable
24	18.38	53.66	10.78	1300	0.46	0.54	0.36	0.32	3	2	3	Just Acceptable
25	22.84	24.54	10.44	1729	0.57	0.25	0.35	0.43	3	2	3	Just Acceptable
26	24.44	24.47	19.40	1450	0.61	0.24	0.65	0.36	3.67	2	3	Just Acceptable
27	12.19	30.70	23.61	2346	0.30	0.31	0.79	0.59	3	1	2	Not Acceptable
28	25.45	62.69	17.37	2232	0.64	0.63	0.58	0.56	3	2	3	Just Acceptable
29	20.27	41.79	7.81	1268	0.51	0.42	0.26	0.32	4	3	4	Acceptable
30	12.87	31.42	11.98	2160	0.32	0.31	0.40	0.54	3	2	3	Just Acceptable

Table 5.2 Simulation of FLC-based IAQ assessment for possible crisp output values

Trials	Indoor Air Quality Parameters	Input Values	Input Values (Normalized)	Crisp Output (Air and Gaseous Parameters)	Air and Gaseous Parameters (Normalized)	Crisp Output (Matlab Fuzzy Logic Toolbox)	Linguistic Classification	True Error
1	Temperature (T)	24	0.6	5	0.91	5	High Acceptable (HA)	0
	Relative Humidity (RH)	44	0.44					
	Carbon Monoxide (CO)	1	0.03	5	0.91			
	Carbon Dioxide (CO2)	200	0.05					
2	Temperature (T)	23	0.58	4.6	0.84	5	Highly Acceptable (HA)	0
	Relative Humidity (RH)	46.4	0.464					
	Carbon Monoxide (CO)	2.5	0.08	5	0.91			
	Carbon Dioxide (CO2)	250	0.06					
3	Temperature (T)	23	0.58	5	0.91	5	Highly Acceptable (HA)	0
	Relative Humidity (RH)	48	0.48					
	Carbon Monoxide (CO)	5	0.17	4	0.73			
	Carbon Dioxide (CO2)	450	0.11					
4	Temperature (T)	27	0.68	3	0.55	4	Acceptable (A)	0
	Relative Humidity (RH)	54	0.56					
	Carbon Monoxide (CO)	4	0.13	4	0.73			
	Carbon Dioxide (CO2)	425	0.11					
5	Temperature (T)	22	0.55	3.75	0.68	4	Acceptable (A)	0
	Relative Humidity (RH)	53	0.53					
	Carbon Monoxide (CO)	8	0.27	3	0.55			
	Carbon Dioxide (CO2)	550	0.14					
6	Temperature (T)	21	0.52	3	0.55	3	Just Acceptable (JA)	0
	Relative Humidity (RH)	31	0.31					
	Carbon Monoxide (CO)	8.5	0.28	3	0.55			
	Carbon Dioxide (CO2)	650	0.16					
7	Temperature (T)	15	0.38	2	0.36	2	Not Acceptable (NA)	0
	Relative Humidity (RH)	25	0.25					
	Carbon Monoxide (CO)	14.5	0.48	2	0.36			
	Carbon Dioxide (CO2)	1750	0.44					
8	Temperature (T)	29	0.73	2	0.36	2	Not Acceptable (NA)	0
	Relative Humidity (RH)	61	0.61					
	Carbon Monoxide (CO)	17	0.57	2	0.36			
	Carbon Dioxide (CO2)	800	0.2					
9	Temperature (T)	5	0.13	1	0.18	1	Highly Not Acceptable (HNA)	0
	Relative Humidity (RH)	11	0.11					
	Carbon Monoxide (CO)	26	0.87	1	0.18			
	Carbon Dioxide (CO2)	3500	0.88					
10	Temperature (T)	38	0.95	1	0.18	1	Highly Not Acceptable (HNA)	0
	Relative Humidity (RH)	92	0.92					
	Carbon Monoxide (CO)	19	0.63	1	0.18			
	Carbon Dioxide (CO2)	2100	0.53					

To further verify the accuracy of the formulated rules, the proponent conducted and intentional 10 trials as shown in Table 5.2 to accommodate possible crisp outputs of Highly Acceptable (HA), Acceptable (A), Just Acceptable (JA), Not Acceptable (NA) and Highly Not Acceptable (HNA) and it was verified that the fuzzy based system is working properly in accordance to programmer-defined rules.

6 CONCLUSION

In this paper, the proponent makes use of fuzzy logic in classifying indoor air quality. The paper presents a technique employing fuzzy logic for automatic classifying of indoor air quality system. It presents a cheaper approach to the classification of indoor air quality, which will also apply most likely to the classification of any other related applications. There were three FIS created: Air parameters, Gaseous parameters and Indoor Air Quality assessments. There were four input fuzzy sets and these were normalized and fuzzified using Sugeno-style of FIS. There were 131 fuzzy rules established. The basis for the construction of the membership function were the identified experts and standards set and maintained by ASHRAE standard 55-2010, ASHRAE standard 62.1-2010, EPA and WHO. The FLC-based indoor air quality assessment was simulated using Matlab Fuzzy Logic Toolbox and the data being generated using Excel VBA macro program. The results obtained can be used for possible improvement of indoor air quality in meeting global standards.

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