

## Implementation of the Mamdani Fuzzy Algorithm for Monitoring Server Room Conditions

Bramantyo Wicaksono<sup>1</sup>

<sup>1</sup>Computer Engineering Technology, Faculty of Vocational School, IPB University  
Bramantyo1122@gmail.com

Ridho Albab Mufarid<sup>2</sup>, Ilham Alfianda Fatwa<sup>3</sup>, Radyanka Irza Pramono<sup>4</sup>, Chika Hayya Sabillah<sup>5</sup>,  
Muhammad Faiz Assariy<sup>6</sup>, Rizki Achmad Rifa'i Dwi Warno<sup>7</sup>

<sup>234567</sup>Computer Engineering Technology, Faculty of Vocational School, IPB University

<sup>2</sup>Ridhoalbab335@gmail.com, <sup>3</sup>ilhamalfianda@gmail.com, <sup>4</sup>radyankairza@apps.ipb.ac.id,  
<sup>5</sup>chikahayya\_asabillah@apps.ipb.ac.id, <sup>6</sup>faizmuhammad@apps.ipb.ac.id, <sup>7</sup>rizkiachmadrifai@apps.ipb.ac.id

### Abstract

This study presents the design and simulation of a server room feasibility evaluation system using the Mamdani Fuzzy Logic approach. The system evaluates three environmental parameters: temperature, relative humidity, and airborne particle concentration. A total of 27 IF–THEN rules were developed based on operational considerations and international environmental recommendations. Triangular membership functions were applied to represent normal operating conditions to enhance sensitivity, while trapezoidal functions were used for extreme conditions to ensure response stability under sensor uncertainty. The inference process employed the minimum operator for rule activation, maximum aggregation, and centroid defuzzification to produce a quantitative feasibility score within a 0–100 scale. Simulation results demonstrate that the fuzzy approach provides smoother and more adaptive decision boundaries compared to *crisp* logic, enabling gradual evaluation of transitional environmental conditions. A case study simulation confirmed that variations in humidity and particulate levels significantly influence the final feasibility score, even when temperature remains within the recommended range. Furthermore, rescaling the particle concentration domain (0–200  $\mu\text{g}/\text{m}^3$ ) improved system sensitivity for indoor pollutant monitoring. The proposed system proves effective as a decision-support tool for intelligent server room environmental monitoring.

**Keywords:** Fuzzy Mamdani, server room monitoring, environmental feasibility evaluation, IoT-based monitoring, air quality assessment.

### INTRODUCTION

The rapid growth of digital services has increased the demand for reliable data center and server infrastructure. To ensure stable operation, server rooms must maintain controlled environmental conditions, particularly temperature and humidity. Improper environmental management can lead to overheating, increased energy consumption, performance degradation, and eventually system downtime (Setyo et al., 2025). Therefore, maintaining appropriate environmental conditions is essential for sustaining server reliability and operational efficiency.

In addition to thermal conditions, air quality inside server rooms also affects the reliability of electronic equipment. Particulate contamination, especially particles within the 2.5–15  $\mu\text{m}$  range, can enter indoor environments through ventilation systems or external air infiltration. These particles may accumulate on electronic components, obstruct airflow circulation, increase thermal resistance, and accelerate overheating or electrical failure (Saini et al., 2022; Santiago et al., 2020). Consequently, environmental monitoring systems for server rooms should consider multiple parameters simultaneously, including temperature, humidity, and particulate concentration.

The development of Internet of Things (IoT) technology enables real-time environmental monitoring through the integration of distributed sensors and communication networks. IoT-based monitoring systems continuously collect environmental data and transmit it to processing units for further analysis. However, environmental sensor data are inherently uncertain due to noise, measurement fluctuations, and dynamic environmental changes. Low-cost environmental sensors, commonly used in IoT systems, often produce noisy or inconsistent data that may affect decision-making processes (Narayana et al., 2024; Okafor et al., 2024). Therefore, decision-making approaches capable of handling uncertainty and gradual transitions in environmental conditions are required.

Fuzzy logic, particularly the Mamdani inference method, has been widely applied in environmental monitoring and decision-support systems due to its ability to model uncertainty and represent gradual reasoning through linguistic variables and membership functions (Andrianto et al., 2024; Santosa et al., 2021). Instead of producing rigid classifications such as “safe” or “unsafe,” fuzzy systems allow environmental conditions to be evaluated within a continuous feasibility spectrum.

In fuzzy inference systems, the design of membership functions plays a crucial role because it directly influences the fuzzification process and the resulting inference behavior. Different membership function shapes can produce different system responses even when the input values are similar. Previous studies have shown that triangular membership functions may produce faster responses but tend to introduce overshoot, while trapezoidal membership functions can provide more stable outputs with lower fluctuations (Chotikunann et al., 2025; Khairuddin et al., 2021). These findings indicate that the selection and configuration of membership functions significantly affect fuzzy system performance.

However, despite the extensive application of Mamdani fuzzy systems in environmental monitoring, most studies primarily focus on system implementation and performance evaluation, while limited attention has been given to analyzing how different membership function shapes influence inference outcomes and decision characteristics (Ahmad et al., 2025; Andrianto et al., 2024; Qomaruddin et al., 2024). In particular, systematic analysis of the impact of triangular and trapezoidal membership functions on environmental feasibility evaluation in server room monitoring systems remains limited.

Therefore, this study aims to simulate and analyze a server room environmental feasibility evaluation system using the Mamdani fuzzy inference method with variations in membership function shapes. Specifically, this research compares triangular and trapezoidal membership functions and examines how differences in curve characteristics and domain parameters influence the resulting feasibility evaluation. The scientific contribution of this study lies in providing a structured analysis of membership function design effects on fuzzy inference behavior within the context of IoT-based server room environmental monitoring systems.

## **METHODS**

This study employs a quantitative simulation-based approach by applying the Mamdani-type fuzzy logic method to develop a server room feasibility evaluation system. In general, the research methodology is structured into several stages: identification of server room assessment parameters, design of input and output variables in the form of fuzzy sets, development of a rule base based on technical considerations and operational standard references, implementation of the fuzzy inference system, and analysis of the defuzzification results as the final feasibility value.

The parameters used in this study are represented as linguistic variables in order to accommodate uncertainty and variations in real-world conditions. Each variable is modeled using appropriate membership functions and then processed through fuzzification, rule inference, aggregation, and defuzzification stages to produce a crisp feasibility value. Through this framework, the research methodology is designed to generate a structured and transparent evaluation system

capable of representing technical assessments more flexibly compared to crisp boundary-based approaches.

### Theoretical Foundation of Mamdani Fuzzy Logic

Fuzzy logic is an extension of classical logic that allows an element to have a degree of membership within a continuous interval  $[0,1]$ , rather than being limited to values of 0 or 1. In crisp logic, a condition is strictly defined as either true or false. However, in real-world problems involving linguistic concepts such as “low,” “moderate,” or “high,” the boundaries between categories are not always rigid. Fuzzy logic accommodates this condition through a membership function  $\mu(x) \in [0,1]$ , which represents the degree of membership of a value in a fuzzy set (Kumari, 2025; Saatchi, 2024).

Membership functions may take triangular, trapezoidal, or Gaussian forms, depending on the characteristics of the modeled variable (D’Aniello, 2023). This approach allows transitions between categories to occur gradually. Unlike probability, which represents uncertainty due to random events, fuzzy logic is used to model the vagueness of linguistic concepts (Saki & Faghihi, 2022). In practice, fuzzy logic is widely applied in decision support systems and intelligent control systems because it can translate expert knowledge into computational rule-based structures (Tang & Ahmad, 2024).

The Mamdani inference method is one of the most commonly used approaches within Fuzzy Inference Systems (FIS) for rule-based IF–THEN systems. In this method, both the antecedent and the consequent are expressed in linguistic terms (fuzzy sets), making the rule structure easily interpretable and intuitive (Putri & Saputro, 2021).

In general, the Mamdani inference process consists of five stages. First, fuzzification, which converts numerical inputs into degrees of membership within fuzzy sets. Second, the application of logical operators (commonly AND = minimum, OR = maximum) to determine the firing strength of each rule. Third, implication, which involves truncating the output fuzzy set based on the rule’s truth value. Fourth, aggregation, which combines all fuzzy outputs from each rule into a single unified set. The final stage is defuzzification, which transforms the fuzzy result into a crisp value, for example using the centroid method (Mada et al., 2022; Nasiboglu & Nasibov, 2025).

Compared to the Sugeno method, which uses mathematical functions in the consequent part, the Mamdani method retains linguistic representations until the final stage before defuzzification. Therefore, it is more suitable for decision-making systems that require transparency and ease of interpretation (Shukri & Isa, 2021).

### System Design and Hardware Schematic

In general, the system consists of three main components: the sensor unit, the processing unit, and the output unit. The sensor unit is responsible for reading environmental conditions, the processing unit executes the fuzzy algorithm, and the output unit displays the feasibility evaluation results of the server room.

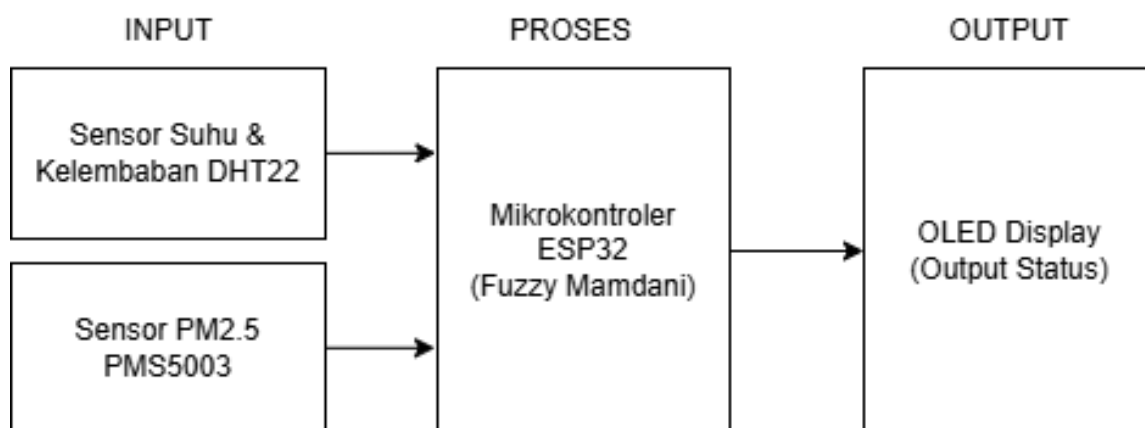


Figure 1. Block Diagram of the Server Room Feasibility Monitoring System

The system hardware is designed to support the environmental data acquisition process of the server room, including temperature, relative humidity (RH), and PM2.5 particulate concentration. These parameters were selected based on recommended environmental conditions for server rooms from ASHRAE TC 9.9 and air cleanliness classifications according to ISO 14644 (ASHRAE TC9.9 Data Center Power Equipment Thermal Guidelines and Best Practices, 2016; IHS, 2015).

The processing unit uses an ESP32 microcontroller, which features a dual-core processor, integrated Wi-Fi interface, and adequate UART and GPIO communication support for IoT-based monitoring systems. The ESP32 is widely used in environmental monitoring research due to its capability in real-time data acquisition and network connectivity (Hercog et al., 2023).

Temperature and relative humidity measurements are performed using the DHT22 sensor. This sensor has a temperature measurement range of  $-40^{\circ}\text{C}$  to  $80^{\circ}\text{C}$  with an accuracy of  $\pm 0.5^{\circ}\text{C}$ , and a humidity range of 0–100% RH with an accuracy of  $\pm 2\text{--}3\%$ . These specifications are considered sufficient for room monitoring applications and have been widely implemented in ESP32-based PM2.5 particulate concentration is measured using the PMS5003 sensor, which operates based on the laser scattering method. This sensor is capable of producing PM1.0, PM2.5, and PM10 concentration outputs in  $\mu\text{g}/\text{m}^3$  units. In various IoT-based air quality monitoring studies, the PMS5003 has been used for real-time particulate trend monitoring, although it is not intended for regulatory calibration purposes (Hura & Monastyrskii, 2023).

Data from the three sensors are read and acquired by the ESP32, then processed using the Mamdani fuzzy method to determine the server room feasibility level based on temperature, humidity, and PM2.5 concentration parameters. This approach is consistent with studies that apply fuzzy logic to evaluate indoor air quality simultaneously using multiple environmental variables (Dionova et al., 2020; Sujono et al., 2023). The processed results are subsequently displayed through a 0.96-inch OLED module (SSD1306) based on I2C as the output unit. The OLED is chosen due to its compact size, low power consumption, and capability to display monitoring parameters in real time, thereby facilitating direct observation of server room conditions (Babiuch & Postulka, 2021).

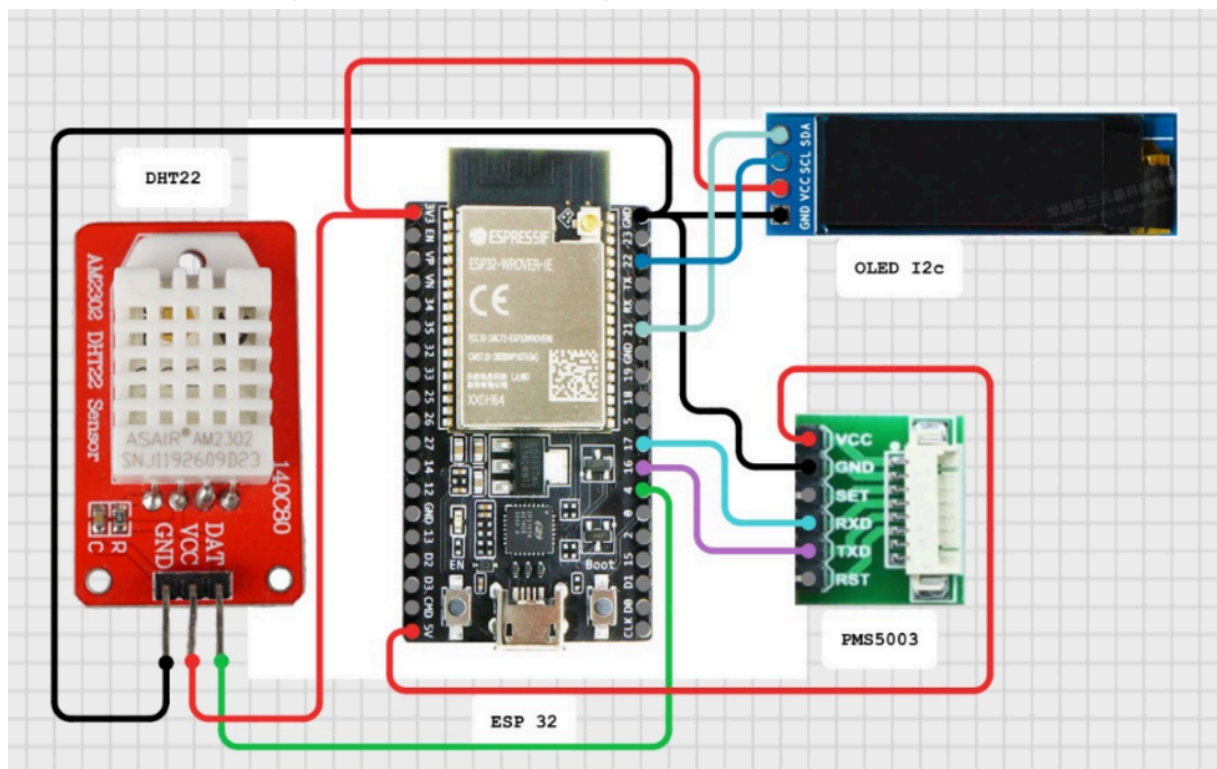


Figure 2. Circuit Schematic of the ESP32-Based Server Room Feasibility Monitoring System

## Variable Identification and Membership Function Design

This study uses three input variables and one output variable within a fuzzy inference system to evaluate the feasibility level of a server room. The selection of variables is based on environmental parameters that directly affect the performance, reliability, and operational lifespan of information technology equipment. These parameters are aligned with international standard recommendations, particularly ASHRAE TC 9.9 for server room thermal conditions and ISO 14644 for air cleanliness monitoring.

Table 1. Universe of Discourse of Variables

Variable	Unit	Range (Universe of Discourse)	Standard Reference
Temperature	°C	15 – 35	ASHRAE TC 9.9
Relative Humidity	%RH	20 – 90	ASHRAE TC 9.9
Air Cleanliness (Particles $\geq 0.5 \mu\text{m}$ )	particles/m <sup>3</sup>	0 – 4.000.000	ISO 14644
Feasibility Level	%	0 – 100	System design

The first input variable is room temperature (°C). Temperature is a critical parameter in IT equipment operation because it directly affects the stability of processors, storage systems, and other electronic components. Based on ASHRAE TC 9.9 recommendations, the suggested operational temperature range for general-class data center environments is 18°C to 27°C. In this study, the universe of discourse for temperature is set from 15°C to 35°C to accommodate possible extreme conditions. The temperature variable is represented by three linguistic categories: low, normal, and high.

Table 2. Temperature Membership Function (°C)

Fuzzy Set	Function Type	Parameters (a, b, c, d)
Low	Trapezoidal	(15, 15, 18, 22)
Normal	Triangular	(18, 23, 27)
High	Trapezoidal	(25, 30, 35, 35)

The second input variable is relative humidity (RH). Humidity plays a role in preventing condensation and electrostatic discharge (ESD), which can damage electronic devices. ASHRAE TC 9.9 recommends a relative humidity range between 20% and 80% RH, with more controlled operational practices typically within 40% to 60% RH. In this study, the universe of discourse for humidity is set between 20% and 90% RH to provide flexibility in evaluating actual conditions. This variable is divided into three linguistic categories: dry, ideal, and humid.

Table 3. Humidity Membership Function

Fuzzy Set	Function Type	Parameters (a, b, c, d)
Dry	Trapezoidal	(20, 20, 30, 40)
Ideal	Triangular	(40, 50, 60)
Humid	Trapezoidal	(55, 70, 90, 90)

The third input variable is air cleanliness level, represented by airborne particle concentration. This parameter refers to air quality monitoring principles as regulated in ISO 14644, which emphasizes the importance of particle contamination control to maintain the reliability of technical environments. Although server rooms are not always classified as cleanrooms, the presence of high particle concentrations can accelerate dust accumulation on equipment and reduce cooling efficiency. In this study, the air cleanliness variable is represented by three linguistic categories: clean, moderate,

and dirty, with value ranges adjusted according to the unit of particle concentration measurement used.

Table 4. Air Cleanliness Membership Function

Fuzzy Set	Function Type	Parameters (a, b, c, d)
Clean	Trapezoidal	(0, 0, 500,000, 1,000,000)
Moderate	Triangular	(500,000, 1,750,000, 3,000,000)
Dirty	Trapezoidal	(2,500,000, 3,200,000, 4,000,000, 4,000,000)

The output variable in this system is the server room feasibility level, expressed on a scale from 0 to 100 percent. This value is obtained through the inference and defuzzification processes of the fuzzy system. To facilitate result interpretation, the output variable is divided into three linguistic categories: not feasible, moderately feasible, and feasible. With this variable structure, the developed system is able to comprehensively represent server room environmental conditions and produce a more adaptive feasibility assessment compared to rigid threshold-based approaches.

Table 5. Output Membership Function

Fuzzy Set	Function Type	Parameters (a, b, c, d)
Not Feasible	Trapezoidal	(0, 0, 30, 50)
Moderately Feasible	Triangular	(40, 60, 75)
Feasible	Trapezoidal	(70, 85, 100, 100)

### Rule Base Development

The rule base is the knowledge component within a fuzzy inference system that consists of a collection of linguistic IF–THEN rules representing expert knowledge and/or data patterns. These rules establish the relationship between combinations of input conditions and output decisions (Varshney & Torra, 2023). In this study, the rules are formulated based on the principle that a server room environment is considered feasible when all parameters fall within optimal ranges according to established standards, and conversely considered not feasible when one or more parameters are in extreme conditions that may endanger IT equipment.

The rules are structured based on the principle of environmental risk prioritization toward server equipment. The temperature parameter is given the most dominant conceptual weight because extreme temperatures (too low or too high) have a direct impact on electronic component stability and cooling efficiency. Therefore, most combinations involving “high” temperature result in a not feasible output, except under conditions where humidity is ideal and air cleanliness is clean, which may still allow the system to operate at a moderately feasible level.

Tabel 6. Rule Base Sistem Fuzzy Kelayakan Ruang Server

No	Temperature	Humidity	Cleanliness	Output
1	Low	Dry	Clean	Moderately Feasible
2	Low	Dry	Moderate	Not Feasible
3	Low	Dry	Dirty	Not Feasible
4	Low	Ideal	Clean	Moderately Feasible
5	Low	Ideal	Moderate	Moderately Feasible
6	Low	Ideal	Dirty	Not Feasible
7	Low	Humid	Clean	Not Feasible
8	Low	Humid	Moderate	Not Feasible
9	Low	Humid	Dirty	Not Feasible
10	Normal	Dry	Clean	Feasible
11	Normal	Dry	Moderate	Moderately Feasible
12	Normal	Dry	Dirty	Not Feasible
13	Normal	Ideal	Clean	Feasible
14	Normal	Ideal	Moderate	Feasible

No	Temperature	Humidity	Cleanliness	Output
15	Normal	Ideal	Dirty	Moderately Feasible
16	Normal	Humid	Clean	Moderately Feasible
17	Normal	Humid	Moderate	Moderately Feasible
18	Normal	Humid	Dirty	Not Feasible
19	High	Dry	Clean	Not Feasible
20	High	Dry	Moderate	Not Feasible
21	High	Dry	Dirty	Not Feasible
22	High	Ideal	Clean	Moderately Feasible
23	High	Ideal	Moderate	Not Feasible
24	High	Ideal	Dirty	Not Feasible
25	High	Humid	Clean	Not Feasible
26	High	Humid	Moderate	Not Feasible
27	High	Humid	Dirty	Not Feasible

The most optimal condition occurs when temperature falls within the normal category and humidity is in the ideal category. Under this combination, if air cleanliness is clean or moderate, the server room is classified as feasible. However, if air cleanliness falls into the dirty category, the feasibility level is downgraded to moderately feasible due to the persistent risk of particle accumulation.

Conversely, if two or more parameters are in extreme conditions (for example, high temperature and humid conditions, or low temperature and dirty air cleanliness), the system directly classifies the condition as not feasible. This approach reflects a conservative principle in server room environmental management, where combinations of multiple risks are not tolerated.

## Inference and Defuzzification Process

### 1. Proses Inferensi

The inference process is carried out by evaluating each IF–THEN rule in the rule base based on the degree of membership of each input variable. In this study, the logical AND operator with the minimum (min) method is used to determine the firing strength or activation level of each rule. Mathematically, if the  $i$ -th rule has the following form:

IF (Temperature= A) AND (Humidity= B) AND (Cleanliness= C) THEN (Feasibility= D)

the activation value is calculated using the equation:

$$\alpha_i = \min(\mu_A(x), \mu_B(y), \mu_C(z))$$

where  $\mu_A(x)$  represents the degree of membership of temperature in set A,  $\mu_B(y)$  represents the degree of membership of humidity in set B, and  $\mu_C(z)$  represents the degree of membership of cleanliness in set C. The value of  $\alpha_i$  is then used to perform clipping on the output membership function according to the activated rule.

### 2. Aggregation Process

After all rules are evaluated, the aggregation process is performed to combine all rule implication results into a single fuzzy output set. In this study, the maximum (max) method is used to combine the results of each rule. Mathematically, the aggregated output membership function is expressed as:

$$\mu_{\text{output}}(z) = \max(\alpha_1, \alpha_2, \dots, \alpha_n)$$

with  $n = 27$  rules.

The max method is selected because it aligns with the characteristics of the Mamdani system, which considers the strongest contribution from active rules in determining the final shape of the output curve.

### 3. Defuzzification Process

The final stage is defuzzification, which converts the aggregated fuzzy set into a crisp value. This study uses the Centroid (Center of Gravity) method because it produces a representative value of the entire fuzzy area distribution and is known for its stability in Mamdani-based evaluation systems. Mathematically, the crisp value is calculated using the equation (Ismarnita & Respitawulan, 2023):

$$Z^* = \frac{\int z \cdot \mu_{output}(z) dz}{\int \mu_{output}(z) dz}$$

Where  $Z^*$  is the crisp feasibility value of the server room,  $z$  is the output variable, and  $\mu_{output}(z)$  is the aggregated membership degree. The centroid method is chosen because it provides stable results and is the most commonly used approach in Mamdani-based fuzzy evaluation systems. The final value obtained lies within the range of 0–100 percent and is used as a quantitative indicator of the server room feasibility level.

## RESULTS AND DISCUSSION

### Membership Function Modeling Results

Each input and output variable is defined in the form of membership functions based on the numerical parameters designed in the methodology stage. The determination of parameters  $a$ ,  $b$ ,  $c$ , and  $d$  was carried out by considering the operational ranges recommended by the ASHRAE TC 9.9 standard for temperature and humidity, as well as ISO 14644 references for air cleanliness based on particle concentration.

Table 7. Input and Output Membership Function Parameters

Variable	Parameter	a	b	c	d	Type	Min	Max
Temperature (Input)	Low	15	15	18	22	Trapezoidal	15	22
	Normal	18	23	27	–	Triangular	18	27
	High	25	30	35	35	Trapezoidal	25	35
Relative Humidity (Input)	Dry	20	20	30	40	Trapezoidal	20	40
	Ideal	40	50	60	–	Triangular	40	60
	Humid	55	70	90	90	Trapezoidal	55	90
Air Cleanliness (Input)	Clean	0	0	500000	1000000	Trapezoidal	0	1000000
	Moderate	500000	1750000	3000000	–	Triangular	500000	3000000
	Dirty	2500000	3200000	4000000	4000000	Trapezoidal	2500000	4000000
Feasibility Level (Output)	Not Feasible	0	0	30	50	Trapezoidal	0	50
	Moderately Feasible	40	60	75	–	Triangular	40	75
	Feasible	70	85	100	100	Trapezoidal	70	100

It can be observed that each variable has three fuzzy sets that overlap with one another. This overlapping is intended to avoid rigid boundaries between categories, allowing the system to represent transitional conditions gradually. For example, in the temperature variable, the range of 18°C to 27°C lies within the transition area between the low and normal categories, as well as between normal and high. This enables the system to generate more flexible decisions compared to conventional classification methods based on discrete thresholds.

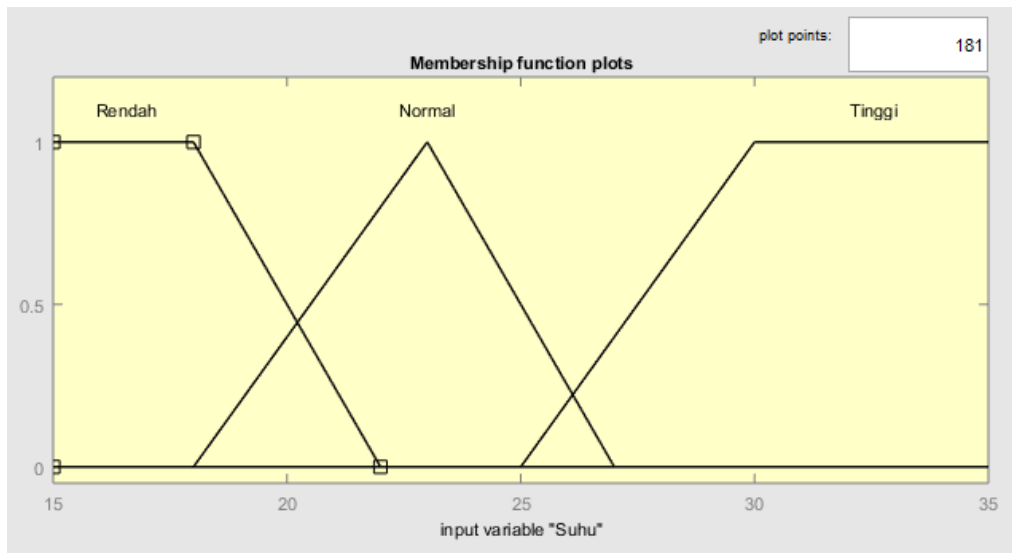


Figure 3. Temperature Input Graph

The temperature membership function graph shows three categories: low, normal, and high. The low category uses a trapezoidal function within the range of 15–22°C, representing temperatures below the optimal operational limit of a server room. The normal category uses a triangular function with a peak at 23°C and a range of 18–27°C, which corresponds to the recommended temperature conditions for maintaining equipment stability. The high category uses a trapezoidal function in the range of 25–35°C, representing conditions that pose a risk of excessive heat buildup.

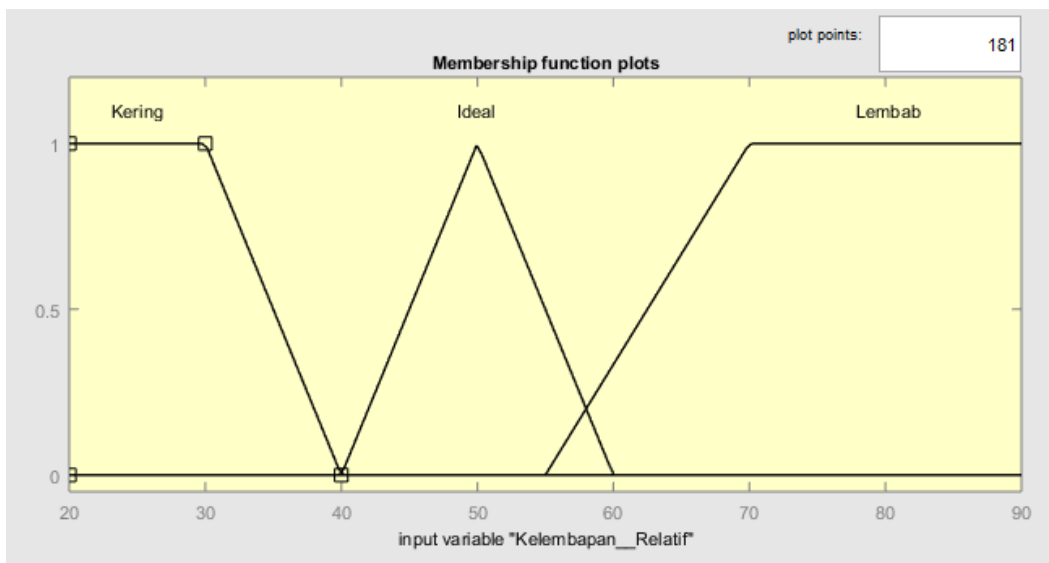


Figure 4. Relative Humidity Input Graph

The relative humidity membership function graph is divided into three categories: dry, ideal, and humid. The dry category uses a trapezoidal function within the range of 20–40% RH, representing conditions that may lead to electrostatic discharge capable of disturbing electronic devices. The ideal category uses a triangular function centered at 50% RH with a range of 40–60% RH, representing stable conditions for a server room. The humid category uses a trapezoidal function within the range of 55–90% RH, which poses risks of condensation and corrosion.

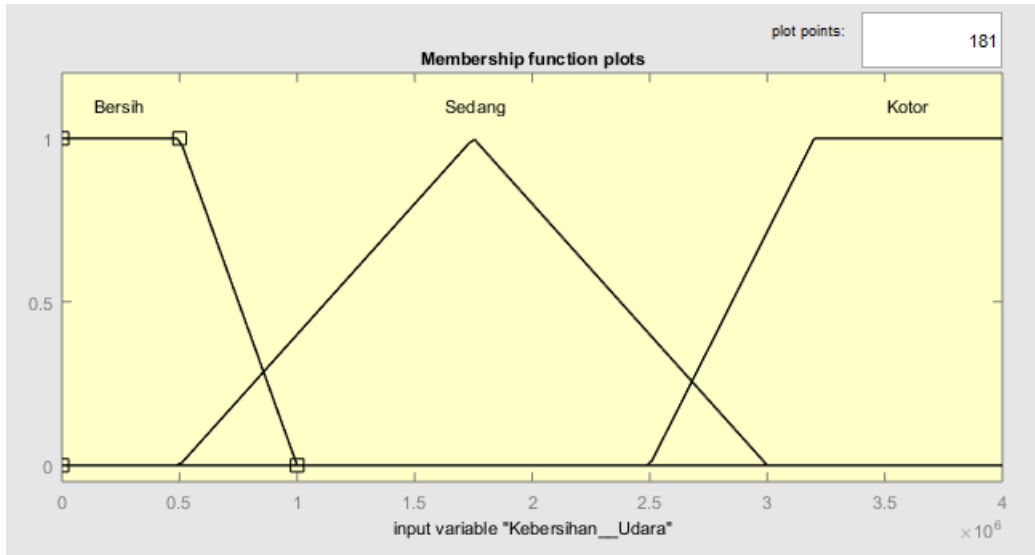


Figure 5. Air Cleanliness Input Graph

The air cleanliness membership function graph is based on particle concentration and divided into three categories: clean, moderate, and dirty. The clean category uses a trapezoidal function within the range of 0–1,000,000 particles/m<sup>3</sup>. The moderate category uses a triangular function within the range of 500,000–3,000,000 particles/m<sup>3</sup>. The dirty category uses a trapezoidal function within the range of 2,500,000–4,000,000 particles/m<sup>3</sup>.

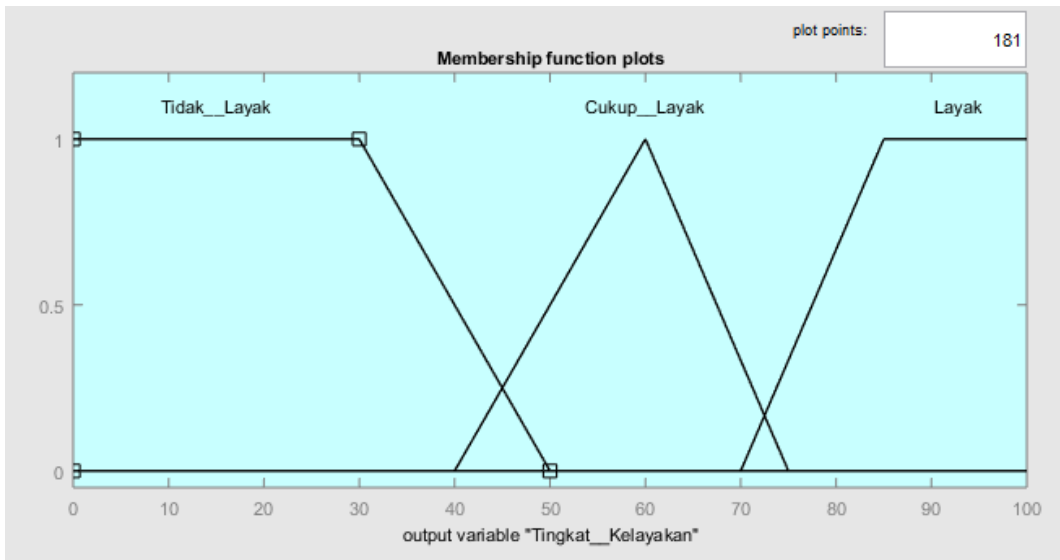


Figure 6. Feasibility Level Output Graph

The output membership function graph consists of three categories: not feasible, moderately feasible, and feasible. The not feasible category uses a trapezoidal function within the range of 0–50%. The moderately feasible category uses a triangular function within the range of 40–75%. The feasible category uses a trapezoidal function within the range of 70–100%. This structure represents percentage values obtained through the defuzzification process. The resulting value quantitatively reflects the feasibility level of the server room and can therefore serve as a measurable basis for decision-making.

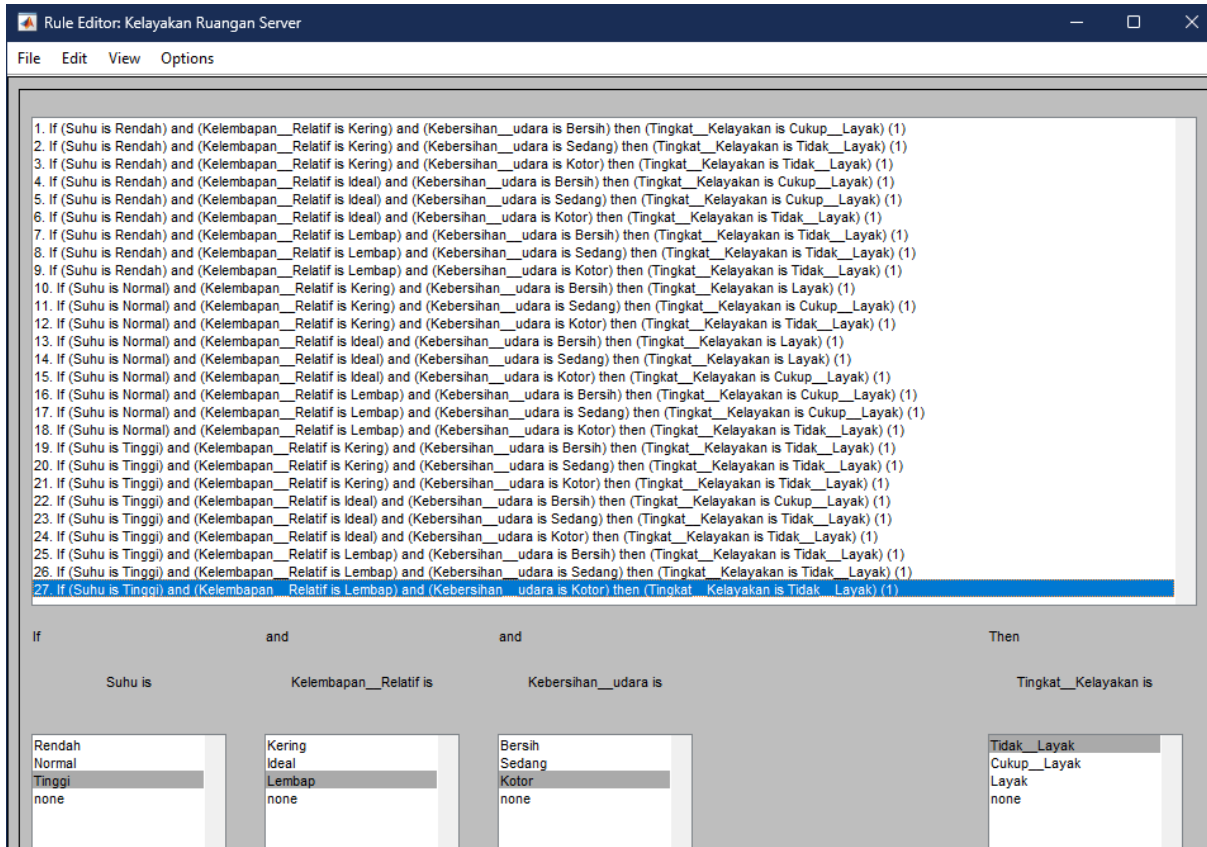


Figure 7. Rule Definition in MATLAB Fuzzy Logic Toolbox

In this system, 27 rules were established from the combination of three input variables (Temperature, Relative Humidity, and Air Cleanliness), each having three fuzzy sets. Each rule is structured in the form of an IF–THEN statement using the AND operator (minimum method) with a rule weight of 1, ensuring that all combinations of server room environmental conditions are systematically covered. The defined rules represent the feasibility evaluation principle, where optimal conditions produce the “Feasible” category, transitional conditions produce the “Moderately Feasible” category, and combinations of parameters that do not meet standards result in the “Not Feasible” category.

### Case Calculation Simulation

To validate the implementation of the designed Mamdani Fuzzy algorithm, a calculation simulation was conducted using a sample server room condition. The input data used are as follows:

- Temperature: 24°C (condition between Normal and High)
- Relative Humidity: 65% RH (condition between Ideal and Humid)
- Air Cleanliness: 750,000 particles/m<sup>3</sup> (condition between Clean and Moderate)

#### 1. Fuzzification Stage

At this stage, the crisp sensor values are converted into membership degrees ( $\mu$ ) based on the predefined membership functions:

- Temperature Variable (24° C):

$$\mu_{\text{Normal}}(24) = \frac{27-24}{27-23} = 0,75.$$

$$\mu_{\text{High}}(24) = 0 \text{ (because the lower boundary of the High category is 25°C)}$$

- Humidity Variable (65%)

$\mu_{\text{Ideal}}(65) = 0$  (because the upper limit of the Ideal category is 60%)

$$\mu_{\text{Humid}}(65) = \frac{65-55}{70-55} = 0,67.$$

- Cleanliness Variable (750,000 particles/m<sup>3</sup>)

$$\mu_{\text{Clean}}(750\text{rb}) = \frac{1.000.000-750.000}{1.000.000-500.000} = 0,50.$$

$$\mu_{\text{Moderate}}(750\text{rb}) = \frac{750.000-500.000}{1.750.000-500.000} = 0,20.$$

## 2. Inference and Aggregation Stage

Based on the rule base (Table 6), two rules are activated for this input combination:

- Rule 16

IF Temperature is Normal AND Humidity is Humid AND Cleanliness is Clean  
THEN Feasibility is Moderately Feasible

$$\alpha_1 = \min(\mu_{\text{Normal}}, \mu_{\text{Humid}}, \mu_{\text{Clean}}) = \min(0,75; 0,67; 0,50) = 0,50.$$

- Rule 17

IF Temperature is Normal AND Humidity is Humid AND Cleanliness is Moderate  
THEN Feasibility is Moderately Feasible

$$\alpha_2 = \min(\mu_{\text{Normal}}, \mu_{\text{Humid}}, \mu_{\text{Moderate}}) = \min(0,75; 0,67; 0,20) = 0,20.$$

Through aggregation using the maximum method:

$$\mu_{\text{ModeratelyFeasible}} = \max(\alpha_1, \alpha_2) = \max(0,50; 0,20) = 0,50$$

## 3. Defuzzification Stage

After inference and aggregation, the final membership degree for the output Moderately Feasible is:

$$\mu_{\text{ModeratelyFeasible}} = 0,50$$

This means that the “Moderately Feasible” output membership function is clipped at a height of 0.50 according to the Mamdani minimum implication method.

- Output Membership Function Shape

The “Moderately Feasible” output membership function is triangular with parameters:  $a = 40$ ,  $b = 60$ , dan  $c = 75$ , Thus:

$$\mu(z) = \left\{ \begin{array}{l} 0, \quad z < 40 \\ \frac{z-40}{60-40}, \quad 40 \leq z \leq 60 \\ \frac{75-z}{75-60}, \quad 60 \leq z \leq 75 \\ 0, \quad z > 75 \end{array} \right.$$

Since the aggregation result is 0.50, the curve is clipped at height 0.50.

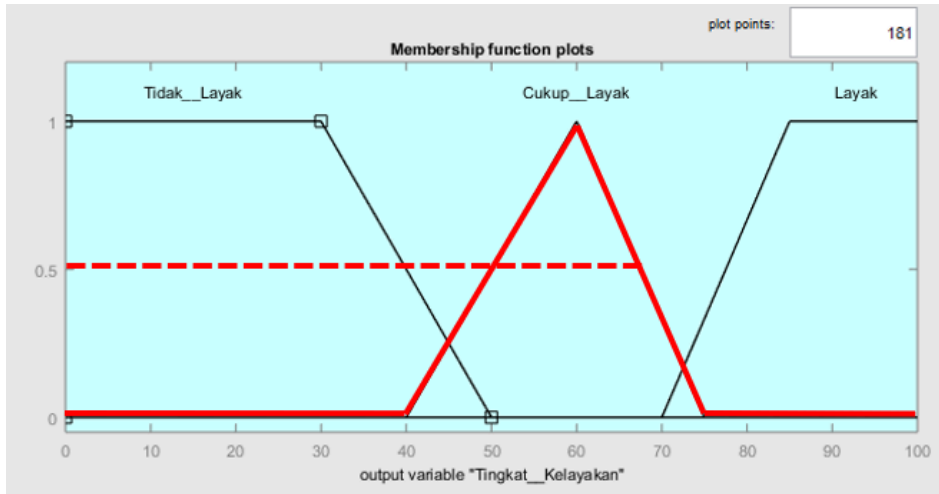


Figure 8. Intersection of the Curve on the Feasibility Level Output

- Determining the Clipping Points

Rising Side (40–60):

$$\frac{z-40}{20} = 0,50$$

$$z - 40 = 10$$

$$z = 50$$

Falling Side (60–75):

$$\frac{75-z}{15} = 0,50$$

$$75 - z = 7,5$$

$$z = 67,5$$

Thus, the clipped region forms a partially symmetric trapezoid between  $z = 50$  and  $z = 67.5$ .

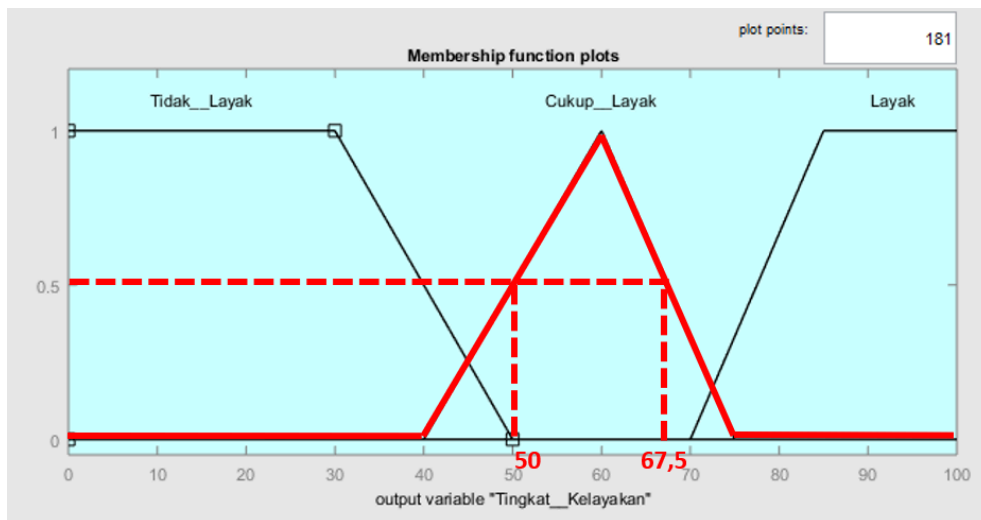


Figure 9. Clipping Points on the Feasibility Level Output

- Centroid Calculation

The next stage is converting the fuzzy value into a crisp value using the Centroid method:

$$Z^* = \frac{\int z \cdot \mu_{\text{output}}(z) dz}{\int \mu_{\text{output}}(z) dz}$$

Since the resulting shape is a partially symmetric trapezoid, it can be calculated using the moment of area approach.

Area 1 (40–50):

$$L_1 = \frac{(50-40) \times 0,50}{2} = 2,5$$

Area 2 (50-67,5):

$$L_2 = (67,5 - 50) \times 0,50 = 8,75$$

Area 3 (67,5-75):

$$L_3 = \frac{(75-67,5) \times 0,50}{2} = 1,875$$

- Perhitungan Momen

The function occurring in the “Feasibility Level” graph appears only in the “Moderately Feasible” parameter. Based on this condition, the membership function is defined as follows:

$$\mu(z, a, b, c) = \begin{cases} 0, & z < 40 \\ \frac{z-40}{60-40}, & 40 \leq z \leq 50 \\ 0,05z - 2, & 50 \leq z \leq 67,5 \\ 0,50 - \frac{75-z}{75-60}, & 67,5 \leq z \leq 75 \\ 0, & z > 75 \end{cases}$$

Next, the moment for each region is calculated using the following formula:

$$M = \int_a^b F_{(z)} z \cdot dz$$

Moment of Region 1:

$$M1 = \int_{40}^{50} (0,05z - 2)z \cdot dz = \int_{40}^{50} 0,05z^2 - 2z \cdot dz = \left[ \frac{z^3}{60} - z^2 \right]_{40}^{50}$$

$$M1 = 116,666$$

Moment of Region 2:

$$M2 = \int_{50}^{67,5} (0,50)z \cdot dz = \left[ \frac{z^2}{4} \right]_{50}^{67,5}$$

$$M2 = 514,0625$$

Moment of Region 3:

$$M3 = \int_{67,5}^{75} (5 - 0,0666z)z \cdot dz = \int_{67,5}^{75} 5z - 0,0666z^2 \cdot dz$$

$$= \left[ \frac{5z^2}{2} - \frac{111}{5000}z^3 \right]_{67,5}^{75}$$

$$M3 = 133,790625$$

Defuzzification uses the Centroid method with the AND operator applied in the inference stage. The defuzzification result is calculated as follows:

$$Z^* = \frac{\int z \cdot \mu_{output}(z) dz}{\int \mu_{output}(z) dz} = \frac{\text{Total Momen}}{\text{Total Luas Daerah}}$$

$$Z^* = \frac{M1+M2+M3}{L1+L2+L3}$$

$$Z^* = \frac{116,6666+514,0625+133,790625}{2,5+8,75+1,875}$$

$$Z^* \approx 58,24912 \approx 58,25\%$$

Based on the calculation of the “Moderately Feasible” output membership function (domain 40–75%), the defuzzification process produces a feasibility value of:

$$Z^* \approx 58,25\%.$$

This result indicates that the evaluated server room condition falls within the Moderately Feasible category with a feasibility level of approximately 58.25%.

## 4. Results Analysis

The evaluation results indicate that although the temperature is predominantly in the normal category (0.75), the increase in humidity to the humid level (0.67) significantly reduces the server room feasibility level to 58.25%. This is consistent with the classification defined in the membership function formulation section, where values within the 40–70 range are categorized as Moderately Feasible.

The combination of triangular and trapezoidal membership curves has proven to provide a stable response. The trapezoidal curves used for extreme conditions ensure that the system continues to provide early warnings when environmental parameters begin to deviate from the ideal thresholds defined by ASHRAE standards.

### Device Implementation Simulation

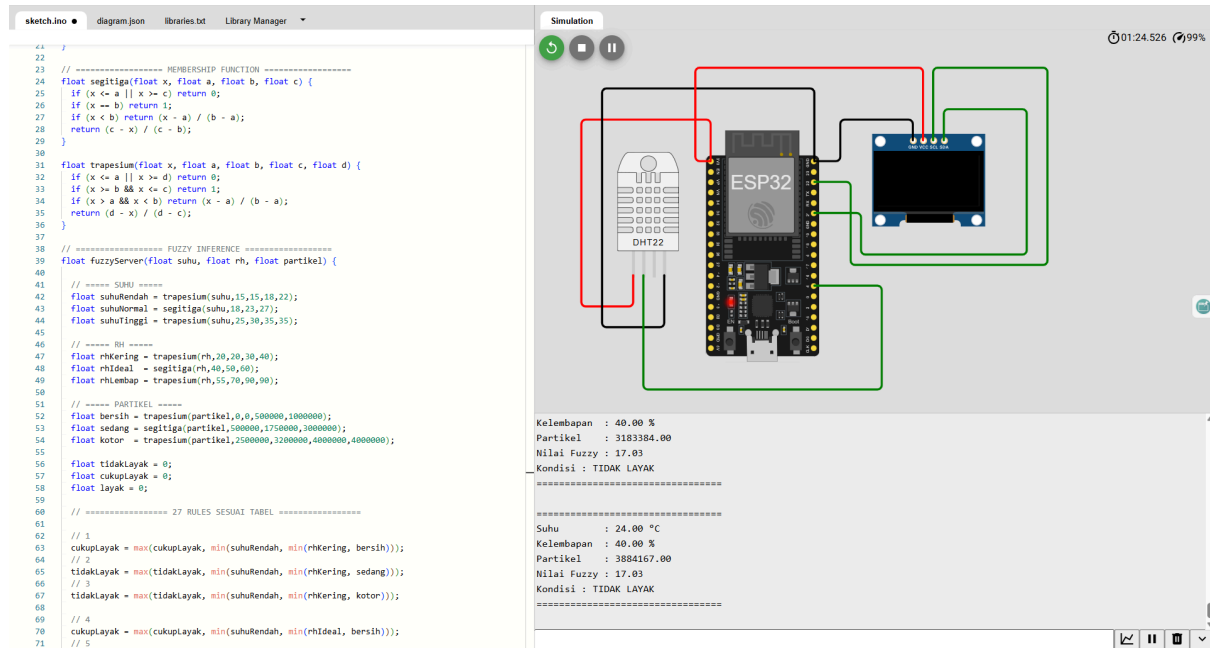


Figure 10. Feasibility Level Output Graph

This simulation was conducted on the Wokwi platform using an ESP32 as the main processor, a DHT22 sensor for temperature and humidity measurement, and a 0.96-inch I2C-based OLED module for display output. Since the PMS5003 sensor is not available on the Wokwi platform, the air cleanliness parameter was not directly implemented through hardware simulation. To address this limitation, the particle concentration value was represented as a variable within the ESP32 program code.

The program begins with the initialization of the libraries used for the DHT22 sensor and the OLED display. The system then periodically reads temperature and humidity values. The particle value represented in the code is combined with the other parameters to form the three fuzzy system inputs. Next, the program calculates the membership degrees of each variable based on the defined membership functions, then evaluates the 27 rules in the rule base to determine the feasibility level. The results of each rule are aggregated, and the final value is calculated using the centroid defuzzification method to obtain a feasibility percentage. This value is then classified into three

categories: Feasible, Moderately Feasible, and Not Feasible, and subsequently displayed on the OLED screen.

## CONCLUSION

Based on the design and simulation results, it can be concluded that the implementation of Mamdani Fuzzy logic through modified membership functions is capable of producing a smoother and more representative assessment of server room feasibility compared to a crisp logic approach. The combination of triangular curves under normal conditions enhances system sensitivity in detecting parameter changes, while the use of trapezoidal curves under extreme conditions provides response stability against sensor data uncertainty.

The implementation of 27 hierarchical rule bases has proven effective in mitigating the risk of equipment damage caused by high temperatures (overheating), extreme humidity (short circuits or electrostatic discharge), and fine dust particle accumulation (PM<sub>2.5</sub>). The centroid defuzzification process produces a quantitative value within the 0–100 range, which is then classified into three feasibility categories. Furthermore, optimization through re-scaling the dust particle variable within the 0–200 µg/m<sup>3</sup> range improves system sensitivity in detecting specific pollutant fluctuations inside the server room compared to using the standard outdoor air quality range.

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