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Computational Analysis of Mamdani Fuzzy Logic on Microcontrollers for Broiler Coop Microclimate Status

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Abstract

High mortality and low productivity in broiler poultry are often caused by poor microclimate conditions, specifically extreme fluctuations in temperature, humidity, and ammonia levels. Therefore, this research aims to develop and validate a computational framework using the Mamdani Fuzzy Inference System to effectively regulate the microclimate within broiler coops. The proposed system utilizes three input variables Temperature, Humidity, and Ammonia to determine two output variables Fan Speed and Coop Safety Status based on 27 logical rules. The defuzzification process employs the Center of Gravity (COG) method. Before hardware implementation on microcontrollers, the system's logic was validated by comparing manual mathematical computations with simulations using MATLAB software. The analysis of the results demonstrated a high degree of precision in the computational model. Manual calculations yielded an output value of 22.62, while the MATLAB simulation produced 22.60. This comparison resulted in an extremely low error rate (deviation) of only 0.088%. These findings confirm that the proposed fuzzy logic architecture is highly accurate, reliable, and strongly recommended for integration into Internet of Things (IoT) ecosystems for real-time agricultural automation.

Keywords: Broiler Chicken, Defuzzification, Mamdani Fuzzy, Microclimate, Microcontroller

INTRODUCTION

The agricultural sector, particularly broiler chicken farming, demands rigorous environmental management to optimize yield and minimize mortality. Broilers are highly susceptible to microclimate dynamics, where extreme deviations in ambient heat, moisture levels, and toxic gas concentrations can induce severe physiological stress (Novaliandra et al., 2026; Syafar, 2018). Specifically, the accumulation of ammonia, a byproduct of poultry excrement, combined with inadequate thermal regulation, is a primary catalyst for respiratory diseases and stunted growth in flocks (Rosikin & Amalia, 2023). Conventional farming mechanisms frequently depend on human intervention or binary automation protocols, which lack the capacity to execute transitional, adaptive responses to subtle environmental shifts.

Previous scholarly investigations have extensively explored the integration of the Internet of Things (IoT) in agricultural and environmental ecosystems. Several studies have deployed basic sensor networks to transmit environmental data, allowing real-time remote monitoring (Ramadhanti et al., 2025; Simangunsong et al., 2025; Wibowo et al., 2022). Furthermore, the application of artificial intelligence, specifically fuzzy logic, has been proposed to handle the non-linear complexities of environmental control. Prior research highlights the efficacy of Mamdani, Tsukamoto, and Sugeno fuzzy architectures in automation systems across various domains, ranging from room quality monitoring to poultry farming (Arya et al., 2024; Bala et al., 2022; Fahila et al., 2024; Gunadi et al., 2021). These studies predominantly focus on adjusting fan speeds or lighting based on singular or dual parameters, primarily temperature and humidity (Amrulloh, M. Faishol Syarwani, 2023; Ariefin et al., 2023; Nasution, Amir S.K. Rijal Nurcahyo & Ramadhanu, 2024). Additionally, fuzzy logic implementations have shown significant reliability in automated irrigation and home comfort systems, demonstrating their broad adaptability (Muttaqi et al., 2024; Satria & Hadi, 2024; Yanto & Afroni, n.d.).

Despite these technological advancements, a significant gap remains in the methodological validation prior to hardware deployment. Most existing models immediately embed computational logic into microcontrollers without conducting rigorous mathematical pre-validation, leading to potential calibration errors and hardware trial-and-error (Aini et al., n.d.; Iksan et al., 2022; Ninggolan, Tia Yohana Oktavianita et al., 2024). Moreover, the integration of ammonia as a third, equally critical input variable in a comprehensive Mamdani inference system remains underexplored in multi-variable coop automation.

To address this existing gap, this study introduces a novel approach by thoroughly validating a tri-variable Mamdani Fuzzy Inference System computationally before physical IoT implementation. The primary objective of this research is to construct and mathematically verify a 27-rule fuzzy logic architecture encompassing Temperature, Humidity, and Ammonia inputs. By employing the Center of Gravity (COG) defuzzification method, the study aims to comparatively analyze the theoretical manual calculations against MATLAB software simulations (Elfaladonna et al., 2022; Harliana1 & Rahim, 2017). This pre-implementation validation is designed to ensure a near-zero deviation error, thereby providing a highly reliable computational blueprint ready to be seamlessly embedded into C++ based microcontrollers for real-time broiler coop automation (Hasibuan et al., 2023).

METHODS

The research design adopted in this study utilizes a comprehensive experimental framework integrated with a prototyping modeling scheme to realize an intelligent control system within a closed-house broiler poultry environment. Integrating Internet of Things (IoT) technology with artificial intelligence algorithms is considered highly crucial in mitigating microclimate fluctuations that fatally impact poultry mortality (Praing et al., 2025). The operational stages of this research are sequentially represented through the formulation of mathematical membership functions, the construction of hardware topology, the simulation of control rule matrices, and concluding with an exact computational validation that compares the microcontroller's execution against theoretical formulations (Olis & Somantri, 2022).

1. System Architecture and Hardware Infrastructure

   The data processing infrastructure of this architecture is governed by the ESP32 DEVKIT V1 microcontroller. The selection of this specific hardware is predicated on its dual-core computational capabilities, which are exceptionally proficient in executing the complex, high-level floating-point calculations necessitated by fuzzy logic algorithms (Simangunsong et al., 2025). For the environmental data acquisition phase, the system implements a DHT22 sensor to simultaneously read two essential physiological parameters ambient air temperature and relative humidity precision.

   Furthermore, considering the urgent hazard of ammonia gas accumulation in farming areas (Bala et al., 2022; Rosikin & Amalia, 2023), this system strategically accommodates ammonia concentration as a third primary input variable. However, to maintain strict safety standards and isolate exposure to toxic gases during the laboratory calibration phase, the ammonia gas variable is quantifiably simulated through an analog signal injection method utilizing a potentiometer component. This approach is scientifically recognized as valid for testing system reliability in responding to critical threshold indicators without requiring actual toxic gas exposure (Putri et al., 2025).

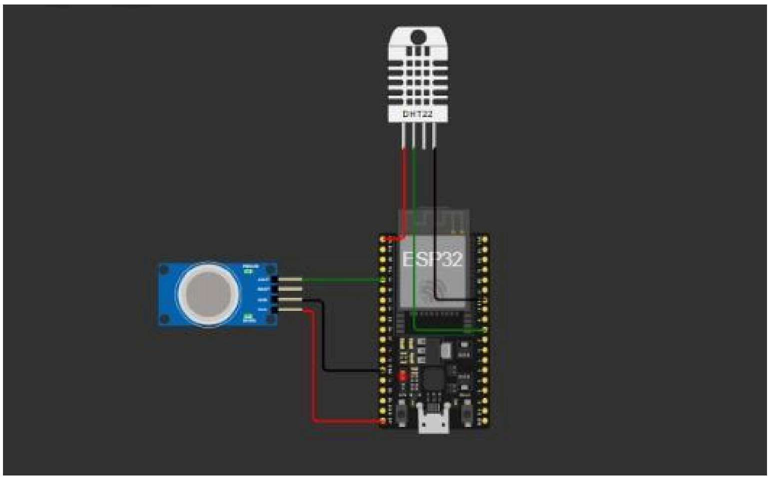


Figure 1. Schematic Design of the Monitoring System

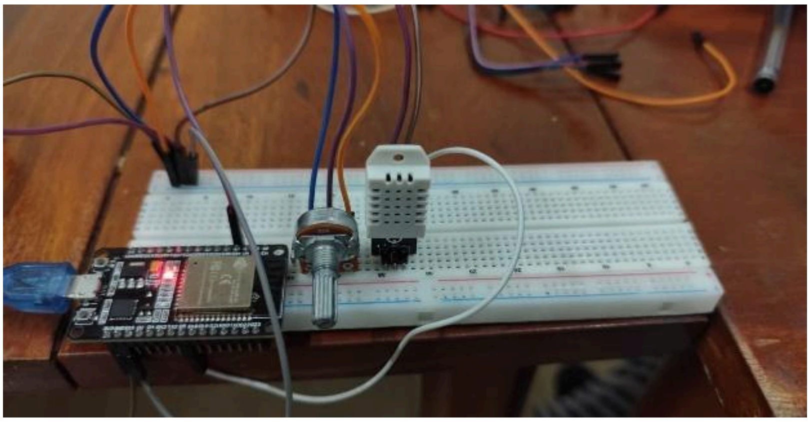


Figure 2. Hardware Implementation for Validation Testing

2. Mamdani Fuzzy Logic Design

   The inference mechanism implemented in this study is the Mamdani Fuzzy model (Max-Min). The Mamdani approach was chosen for its highly intuitive ability to translate human-like reasoning into computational logic, making it exceptionally suited for continuous actuation systems, such as fan motor regulation (Sari et al., 2024; Trinaldi et al., 2022). This design architecture encompasses three critical phases:

   a. Fuzzification

      This phase is responsible for translating the crisp input values obtained from the sensors into predictor membership degrees. The definition of the membership function boundaries is strictly based on the established physiological standards and thermal comfort zones of poultry, as synthesized from the environmental control parameters outlined by Syafar, (2018) and Novaliandra et al., (2026). Consequently, the input and output parameters are categorized into the following universal sets:

      - The Temperature Input Variable is divided into Cold (< 26°C), Normal (28°C - 33°C), and Hot (> 35°C). According to the microclimate management studies by Syafar, (2018) and Novaliandra et al., (2026), maintaining the optimal ambient temperature is critical for broiler metabolic rates and preventing heat stress. Fluctuations outside the normal range can lead to severe panting and increased mortality.
      - The Humidity Input Variable is defined by Dry (< 50%), Moist (60% - 70%), and Wet (> 75%). Based on the referenced literature Syafar, (2018) maintaining relative humidity between 60% and 70% is crucial to prevent

respiratory diseases and control litter moisture, whereas higher humidity significantly exacerbates the perceived heat stress in the coop.

- The Ammonia Input Variable is categorized as Safe (< 10 ppm), Warning (15 - 22 ppm), and Dangerous (> 30 ppm). Furthermore, Novaliandra et al., (2026) emphasize that ammonia concentrations must be strictly monitored and kept at minimum safe levels; prolonged exposure to concentrations exceeding the threshold induces severe health risks, corneal damage, and drastically reduces poultry productivity.
- The Output Variables govern the Fan Speed actuation (Off, Slow, and Fast), Heater intensity (Off, Dim, and Bright), and Coop Comfort Index (Good, Warning, and Bad). During the results comparison phase, this manuscript will specifically focus the analysis on the performance of the Fan Speed and the Comfort Index/Status..

For computational purposes, these set boundaries are mathematically modeled into membership function equations as follows:

1) Air Temperature Input Variable

The temperature membership functions are represented by trapezoidal and triangular curves with the following equations:

a) Cold

$$F_{(X,a,b,c,d)}\{0,\quad x < 20\ 1,\quad 20 \le x \le 26\ \frac{30-x}{30-26},\quad 26 < x < 30\quad 0,\quad x \ge 30$$

b) Normal

$$F_{(X,a,b,c)}\{0,\quad x \le 25\ \frac{x-28}{32-28},\quad 28 \le x < 32\ \frac{35-x}{35-33},\quad 32 \le x < 35\ 0,\quad x \ge 35$$

c) Hot

$$F_{(X,a,b,c,d)}\{0,\quad x \le 33\ \frac{x-33}{36-33},\quad 33 < x < 36\ 1,\quad x \ge 36$$

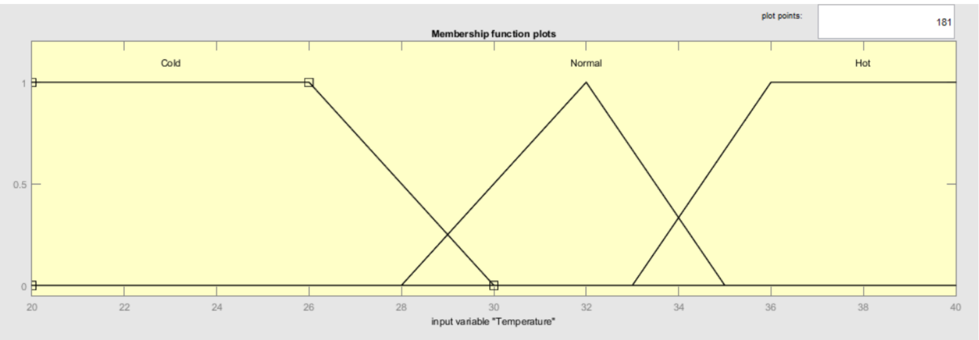


Figure 3. Membership Function Graph for Air Temperature Input

2) Relative Humidity Input Variable

The humidity membership functions are calculated using the following equations:

a) Dry

$$F_{(X,a,b,c,d)}\{0,\quad x < 40\ 1,\quad 40 \le x \le 50\ \frac{60-x}{60-50},\quad 50 < x < 60\quad 0,\quad x \ge 60$$

b) Moist

$$F_{(X,a,b,c)} \{0, \quad x < 55 \ \frac{x-55}{60-55}, \ 55 \le x < 60 \ \frac{70-x}{70-60}, \ 60 \le x < 70 \ 0, \ x \ge 70$$

c) Wet

$$F_{(X,a,b,c,d)} \{0, \quad x \le 65 \ \frac{x-65}{75-65}, \ 65 < x < 75 \ 1, \ x \ge 75$$

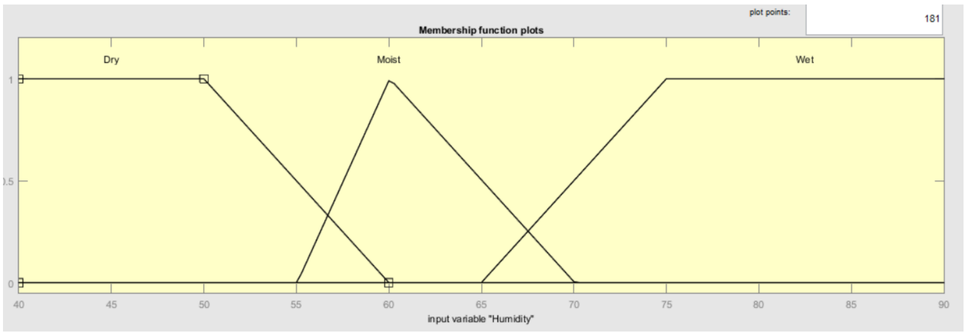


Figure 4. Membership Function Graph for Relative Humidity Input

3) Ammonia Level Input Variable

The ammonia membership functions are formulated as:

a) Safe

$$F_{(X,a,b,c,d)} \{0, \quad x < 0 \ 1, \ 0 \le x \le 10 \ \frac{20-x}{20-10}, \ 10 < x < 20 \ 0, \ x \ge 20$$

b) Warning

$$F_{(X,a,b,c)} \{0, \quad x < 15 \ \frac{x-15}{22-15}, \ 15 \le x < 22 \ \frac{30-x}{30-22}, \ 22 \le x < 30 \ 0, \ x \ge 30$$

c) Dangerous

$$F_{(X,a,b,c,d)} \{0, \quad x \le 25 \ \frac{x-25}{30-25}, \ 25 < x < 30 \ 1, \ x \ge 30$$

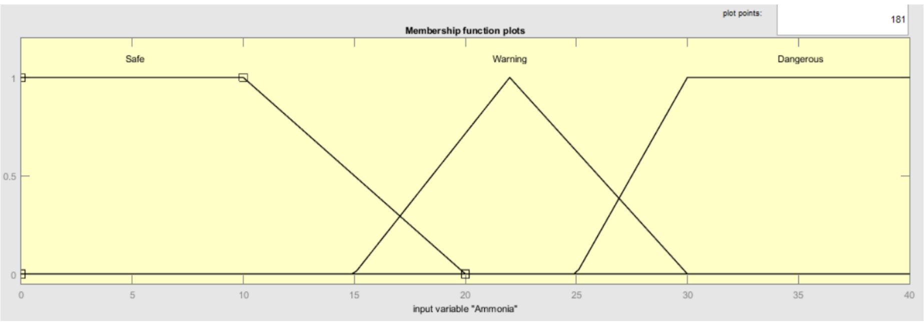


Figure 5. Membership Function Graph for Ammonia Level Input

4) Coop Comfort Index Output Variable

The comfort index membership functions are formulated as:

a) Bad

$$F_{(X,a,b,c,d)} \{0, \quad x < 1 \ 1, \ 30 \le x \le 50 \ \frac{50-x}{50-30}, \ 30 < x < 50 \ 0, \ x \ge 50$$

b) Warning

$$F_{(X,a,b,c)}\{0, \quad x \leq 40 \frac{x-40}{60-40}, \; 40 < x < 60 \frac{80-x}{80-60}, \; 60 < x < 80\,0, \; x \geq 80$$

c) Good

$$F_{(X,a,b,c,d)}\{0, \quad x \leq 70 \frac{x-70}{85-70}, \; 70 < x < 85 \; 1, \; x \geq 85$$

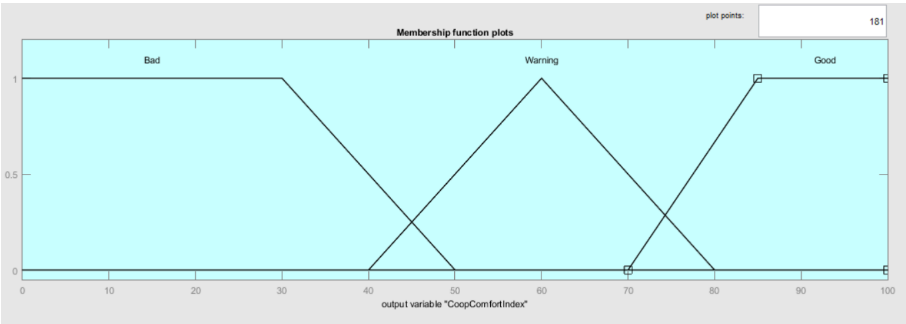


Figure 6. Membership Function Graph for Coop Comfort Index Output

5) Fan Speed Output Variable

The fan speed membership functions are formulated as:

a) Off

$$F_{(X,a,b,c,d)}\{0, \quad x < 20\,1, \; 0 \leq x \leq 5 \frac{20-x}{20-5}, \; 5 < x < 20 \; 0, \; x \geq 20$$

b) Slow

$$F_{(X,a,b,c)}\{0, \quad x \leq 15 \frac{x-15}{40-15}, \; 15 < x < 40 \frac{65-x}{65-40}, \; 40 < x < 65\,0, \; x \geq 65$$

c) Fast

$$F_{(X,a,b,c,d)}\{0, \quad x \leq 60 \frac{x-60}{80-60}, \; 60 < x < 80 \; 1, \; x \geq 80$$

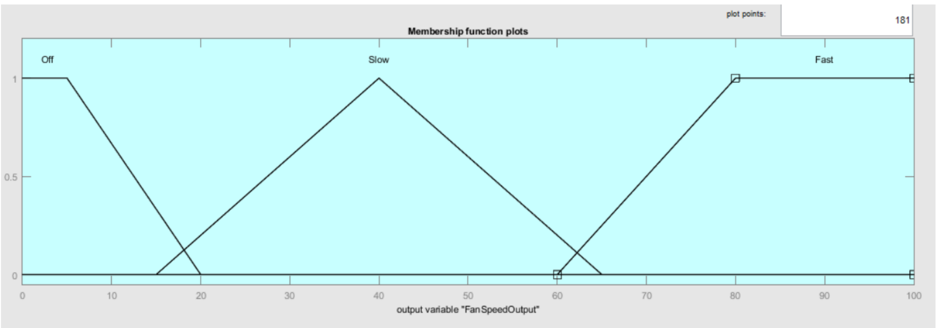


Figure 7. Membership Function Graph for Fan Speed Output

b. Rule Base

The inference process is interwoven using the logical "AND" connective to cross-evaluate the probabilities among variables. The formulation of the 27 foundational rules is not arbitrary; rather, it is synthesized from expert domain knowledge and empirical environmental control matrices established in prior studies, specifically adopting the poultry microclimate management guidelines by Syafar, (2018) and the fuzzy rule architecture proposed by Novaliandra et al., (2026).

The logical framework of these rules is grounded in the following physiological rationales derived from the referenced literature:

- Thermal Regulation (Heater and Fan interaction) As emphasized by Syafar, (2018), when the temperature drops to the "Cold" threshold, the system must prioritize activating the Heater (Bright/Dim) to prevent hypothermia, while maintaining a "Slow" Fan speed to minimize heat loss. Conversely, in "Hot" conditions, the Fan is maximized (Fast) and the Heater is strictly turned Off to dissipate accumulated heat stress.
- Toxicity Override (Ammonia dominance) According to Novaliandra et al., (2026), ammonia concentration acts as a critical and lethal health determinant. Therefore, the matrix is designed so that whenever the Ammonia level reaches the "Dangerous" state, the Fan must operate at "Fast" speed and the Status becomes "Dangerous" to quickly exhaust the toxic gas, often overriding the normal temperature and humidity comfort variables.
- Humidity Synergy High humidity ("Wet") combined with extreme temperatures exacerbates thermal discomfort and respiratory issues. Thus, rules involving "Wet" conditions generally elevate the system's hazard status faster than "Dry" or "Moist" conditions (Syafar, 2018).

Given the 3 predictor parameters (Temperature, Humidity, and Ammonia), each containing 3 linguistic values, the system executes a comprehensive matrix totaling 3 × 3 × 3 = 27 foundational rules. The codification of these rules is detailed as follows:

1) I IF Temperature is Cold AND Humidity is Dry AND Ammonia is Safe THEN Fan is Slow, Heater is Bright, Status is Warning.
2) IF Temperature is Cold AND Humidity is Dry AND Ammonia is Warning THEN Fan is Medium, Heater is Bright, Status is Warning.
3) IF Temperature is Cold AND Humidity is Dry AND Ammonia is Dangerous THEN Fan is Fast, Heater is Dim, Status is Dangerous.
4) IF Temperature is Cold AND Humidity is Moist AND Ammonia is Safe THEN Fan is Slow, Heater is Bright, Status is Safe.
5) IF Temperature is Cold AND Humidity is Moist AND Ammonia is Warning THEN Fan is Slow, Heater is Bright, Status is Dangerous.
6) IF Temperature is Cold AND Humidity is Moist AND Ammonia is Dangerous THEN Fan is Fast, Heater is Off, Status is Dangerous.
7) IF Temperature is Cold AND Humidity is Wet AND Ammonia is Safe THEN Fan is Slow, Heater is Bright, Status is Warning.
8) IF Temperature is Cold AND Humidity is Wet AND Ammonia is Warning THEN Fan is Medium, Heater is Dim, Status is Dangerous.
9) IF Temperature is Cold AND Humidity is Wet AND Ammonia is Dangerous THEN Fan is Fast, Heater is Off, Status is Dangerous.
10) IF Temperature is Normal AND Humidity is Dry AND Ammonia is Safe THEN Fan is Slow, Heater is Off, Status is Warning.
11) IF Temperature is Normal AND Humidity is Dry AND Ammonia is Warning THEN Fan is Medium, Heater is Dim, Status is Dangerous.
12) IF Temperature is Normal AND Humidity is Dry AND Ammonia is Dangerous THEN Fan is Fast, Heater is Off, Status is Dangerous.

13) IF Temperature is Normal AND Humidity is Moist AND Ammonia is Safe THEN Fan is Medium, Heater is Off, Status is Safe.
14) IF Temperature is Normal AND Humidity is Moist AND Ammonia is Warning THEN Fan is Medium, Heater is Off, Status is Warning.
15) IF Temperature is Normal AND Humidity is Moist AND Ammonia is Dangerous THEN Fan is Fast, Heater is Off, Status is Dangerous.
16) IF Temperature is Normal AND Humidity is Wet AND Ammonia is Safe THEN Fan is Medium, Heater is Off, Status is Warning.
17) IF Temperature is Normal AND Humidity is Wet AND Ammonia is Warning THEN Fan is Fast, Heater is Off, Status is Dangerous.
18) IF Temperature is Normal AND Humidity is Wet AND Ammonia is Dangerous THEN Fan is Fast, Heater is Off, Status is Dangerous.
19) IF Temperature is Hot AND Humidity is Dry AND Ammonia is Safe THEN Fan is Fast, Heater is Off, Status is Dangerous.
20) IF Temperature is Hot AND Humidity is Dry AND Ammonia is Warning THEN Fan is Fast, Heater is Off, Status is Dangerous.
21) IF Temperature is Hot AND Humidity is Dry AND Ammonia is Dangerous THEN Fan is Fast, Heater is Off, Status is Dangerous.
22) IF Temperature is Hot AND Humidity is Moist AND Ammonia is Safe THEN Fan is Fast, Heater is Off, Status is Warning.
23) IF Temperature is Hot AND Humidity is Moist AND Ammonia is Warning THEN Fan is Fast, Heater is Off, Status is Dangerous.
24) IF Temperature is Hot AND Humidity is Moist AND Ammonia is Dangerous THEN Fan is Fast, Heater is Off, Status is Dangerous.
25) IF Temperature is Hot AND Humidity is Wet AND Ammonia is Safe THEN Fan is Fast, Heater is Off, Status is Dangerous.
26) IF Temperature is Hot AND Humidity is Wet AND Ammonia is Warning THEN Fan is Fast, Heater is Off, Status is Dangerous.
27) IF Temperature is Hot AND Humidity is Wet AND Ammonia is Dangerous THEN Fan is Fast, Heater is Off, Status is Dangerous.

c. Defuzzification

The compilation of all triggered rule matrices generates a combined aggregation curve. This aggregated curve is subsequently re-extracted into an exact scalar value that the microcontroller can process, utilizing the Center of Gravity (Centroid) method. The programmatic equation embedded to calculate this crisp value aims to determine the equilibrium point of the area (moment divided by area):

$$Z^{*} = \frac{\int \mu(z) \cdot z \, dz}{\int \mu(z) dz}$$

The implementation of the Centroid method enables the output transitions (such as fan rotation) to adapt dynamically and smoothly in response to real-time microclimate modifications.

RESULTS AND DISCUSSION

The implementation of the Mamdani Fuzzy logic modeling framework on the microclimate monitoring prototype has been comprehensively executed and evaluated. This section elucidates the system's design success matrix, which is quantified through three comparative and functional testing approaches. The first phase dissects the algorithmic transition characteristics via surface viewer projections. Subsequently, the second phase highlights the mathematical architectural integrity through an analytical comparison between theoretical calculations and the software simulator. As a final validation, the third phase demonstrates the operational feasibility of the embedded system in real-time, utilizing readings from the microcontroller hardware interface. This structured testing sequence is intended to prove that the embedded rule matrix formulation operates deterministically, precisely, and reliably in mitigating environmental anomalies.

1. Fuzzification Analysis Membership Functions

   The initial phase in the Mamdani Fuzzy computational process is fuzzification. This mechanism involves mapping explicit raw data (crisp inputs) obtained from sensor readings into fuzzy linguistic categories by employing specific membership functions. The developed system accommodates three primary input variables: Temperature, Humidity, and Ammonia.

   a. Temperature Input Variable

      The thermal parameter is segmented into three distinct linguistic subsets Cold, Normal, and Hot. The universe of discourse range for the coop's temperature is established between 20°C and 40°C. The determination of the normal temperature threshold refers to the studies conducted by Syafar, 2018 and Novaliandra et al., 2026, asserting that the ideal thermal stability for poultry rearing lies within the 20°C to 35°C spectrum, depending on the specific growth phase. Consequently, the curve representation for the temperature variable is constructed using a combination of trapezoidal and triangular functions to accurately respond to heat fluctuations occurring outside these optimal boundaries.

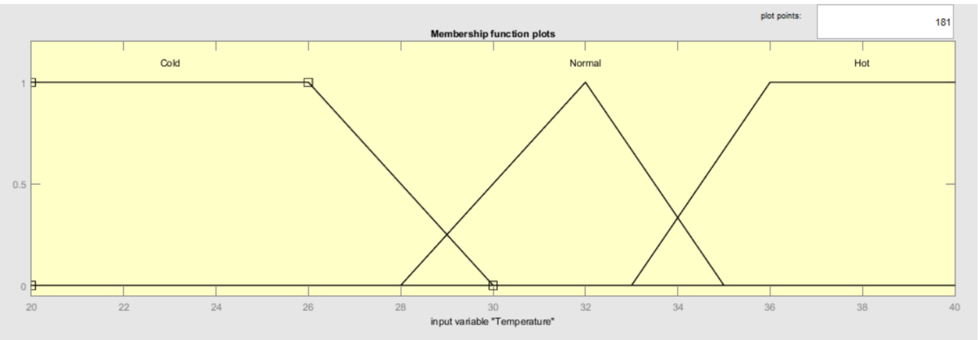


Figure 8. Membership Function Curve for Temperature Input Variable

Based on Figure 8, the membership degree for each specific condition can be calculated using the predetermined mathematical formulations. The selection of this range is fundamentally based on the thermal requirements of broiler chickens during their developmental stages.

   b. Humidity Input Variable

      The second microclimate parameter computed by the system is Relative Humidity (RH). This variable is represented across three linguistic sets Dry, Moist, and Wet, with a percentage universe of discourse bounded from 40% to 90%. Syafar, 2018 and Novaliandra et al., 2026 emphasize that the recommended safe humidity limit for closed-house farming systems ranges from 50% to 80%. The functional curves are meticulously designed to enable the system to respond rapidly whenever the RH reaches extreme levels below 50% or exceeds 80%.

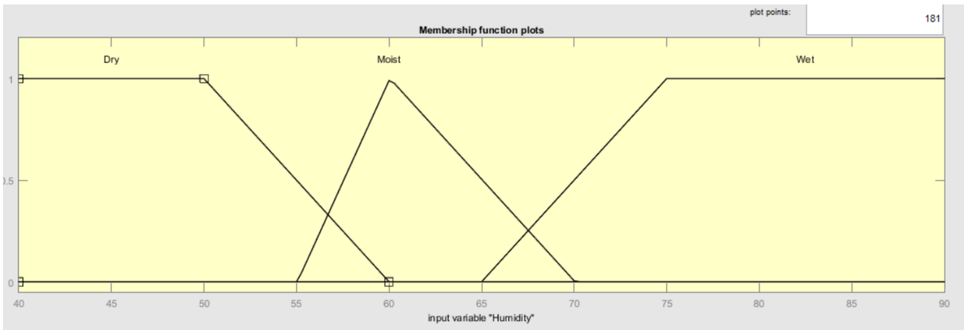


Figure 9. Membership Function Curve for Humidity Input Variable

The curve plotting in Figure 9 demonstrates the intersection among the sets, allowing the system to respond to humidity variations in a smooth and transitional manner, rather than executing binary or rigid switches.

c. Ammonia Level Input Variable

The third input parameter, which serves as a highly crucial factor in preventing poultry mortality, is the concentration of ammonia gas. This specific variable is classified into three linguistic categories Safe, Warning, and Dangerous, with the universe of discourse spanning from 0 to 40 ppm. According to the environmental standards outlined by Novaliandra et al., 2026, the ammonia concentration inside the housing must be strictly maintained below 20 ppm to avoid respiratory disorders in the flock. The visual curve in Figure 10 maps this tolerance boundary, ensuring that the processing unit is capable of detecting warning threshold conditions before the accumulation touches hazardous toxic levels.

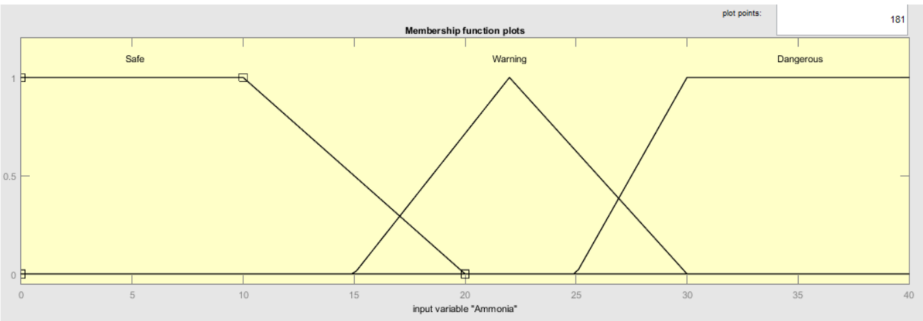


Figure 10. Membership Function Curve for Ammonia Level Input Variable

The visual representation in Figure 10 delineates the tolerance limits for ammonia toxicity exposure. This graphical modeling ensures the processing unit can instantaneously detect early warning conditions, effectively intervening before the toxic gas accumulation can damage the respiratory systems of the poultry.

2. Control Surface Analysis

The decision-making characteristics of the embedded Mamdani Fuzzy Inference System (FIS) architecture can be comprehensively evaluated via a three-dimensional mapping known as the surface viewer. This topological representation is critically important for validating the dynamic interactions between the predictor variables (inputs) and the actuation variables (outputs), while simultaneously verifying the absence of logical anomalies across the rule transition spectrum.

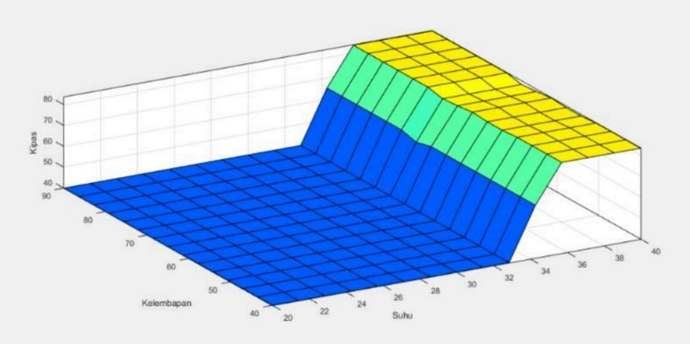


Figure 11. Surface Mapping of Temperature and Humidity Interaction on Fan Speed Percentage

The visual interpretation presented in Figure 11 illustrates a highly structured positive correlation linking thermal and moisture parameters to the exhaust fan's rotational acceleration. It is evident that as the temperature shifts toward the hotter range, accompanied by a surge in relative humidity, the vertical curve (Z-axis) representing the fan speed elevates gradually without exhibiting any chattering effects (sudden mechanical spikes). This smooth mechanical response is exceptionally essential in preserving the thermoregulatory stability of the poultry environment. This behavioral pattern aligns with the findings of Fahila et al., 2024 and Rizal et al., 2024, who confirmed that extreme microclimate fluctuations can provoke severe heat stress and obstruct poultry metabolic processes therefore, an adaptive cooling actuation is critically required to sustain overall productivity.

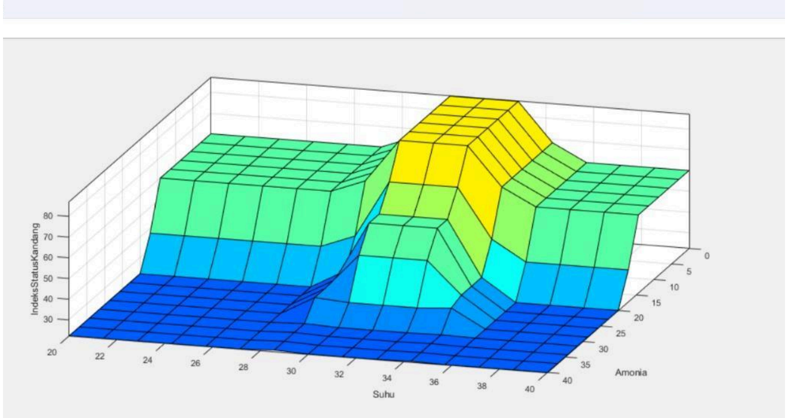


Figure 12. Surface Representation of the Influence of Temperature and Ammonia Levels on Coop Comfort Status

Conversely, the surface topography in Figure 12 highlights the algorithm's heightened sensitivity to ammonia gas contamination. Even when the temperature parameter is recorded in an equilibrium normal state, the graphical surface will instantaneously slope sharply toward the "Dangerous" status if the ammonia concentration breaches the established tolerance threshold > 20 ppm. This algorithmic logic is purposefully designed with a priority on toxicity mitigation, considering that the accumulation of ammonia gas from excreta not only degrades air quality but also possesses the potential to severely damage respiratory tracts and trigger mass mortality in broiler chickens (Arya et al., 2024; Mujiono et al., 2023).

3. Validation of Computational Calculation and Defuzzification Integrity

To guarantee the reliability of the implemented logical framework, a computational comparative test was conducted, aligning the manual mathematical extraction results with the outputs generated by the MATLAB commercial simulator. The random state sampling test specifically focused on an input instrument scenario with the following readings: Temperature 26.90°C, Humidity 65.10%, and Ammonia 23.24 ppm.

Evaluated through the established membership functions, the highest activation degree stimulates the primary governing rule Rule 5, which correlates the premises of Cold Temperature, Moist Humidity, and Warning Ammonia. Through the application of the MIN implication operator, a truth-level truncation value (α) of 0.49 was acquired. This ceiling value is subsequently utilized to truncate the trapezoidal curves on both the Fan Speed and the Coop Comfort Status/Index actuation outputs. The final explicit value crisp output is extracted utilizing the Center of Gravity methodology.

a. Defuzzification Analysis of the Coop Comfort Status Output

Identical to the fan computation sequence, the truncation of the set curve on the Coop Status output specifically within the 'Safe' and 'Warning' intersection at the 0.49 level forms a geometric area construction. This integration process is essential to discover the precise equilibrium point of the system's decision.

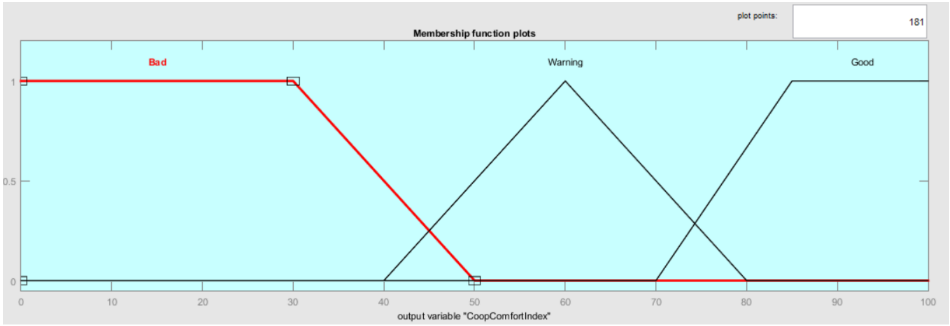


Figure 13. Defuzzification Curve Graph for Coop Status Index Output in MATLAB

1) Total Area Calculation (TLD)

- $LD_{1}, = Right\ Triangle$
- $LD_{1} = \frac{(50-40,2)\times 0,49}{2} = 2,4$
- $LD_{2}, = Rectangle$
- $LD_{2} = 40,2\times 0.49 = 19,698$
- Total Area Calculation (TLD) =
  $LD_{1} + LD_{2} = 2,4 + 19,698 = 22,098$

The Total Area (TLD) represents the cumulative mathematical "weight" of all active fuzzy rules. In this calculation, the resulting area reflects the dominance of the "Safe" status based on the current sensor inputs Temperature, Humidity, and Ammonia. A consistent TLD value ensures that the system has a stable foundation before determining the final numerical output.

2) Static Moment Integral Calculation (M)

- $M1 = \int_{0}^{40,2} 0,49x dx = 0,245\, x^{2} |\frac{40,2}{0} = 395,93$

- $M2 = \int_{40,2}^{50} (2,5 - 0,05x)xdx = \int_{40,2}^{50} \left(2,5x - 0,05x^{2}\right)dx = 1,25x^{2} - 0.016667x$
- Total Moment (TM) = $395,93 + 103,94 = 499,87$

The Static Moment (TM) calculates the distribution of the area's mass relative to the horizontal axis (the 0-100 comfort scale). This value is crucial because it identifies where the "center of gravity" of the environmental condition lies. It acts as the weighted numerator that considers how far the current coop status leans toward a dangerous threshold.

3) Final Value Affirmation (Crisp Output)

The center of mass point for the output area is extracted using the division ratio between the Total Moment (TM) and the Total Area (TLD):

$$Z^{*} = \frac{TM}{TLD} = \frac{499{,}87}{22{,}098} = 22,62$$

The final crisp value of 22.62 serves as the definitive "Coop Comfort Index." Physically, since this value is positioned within the lower segment of the membership function below the 30-50 threshold, it indicates that the coop environment is in a "Safe/Normal" condition. From a control perspective, this number instructs the microcontroller that the microclimate is optimal for the broiler chickens' physiology. Consequently, the actuators (Fans and Heaters) do not need to trigger emergency high-speed ventilation, thereby optimizing energy consumption while maintaining poultry welfare.

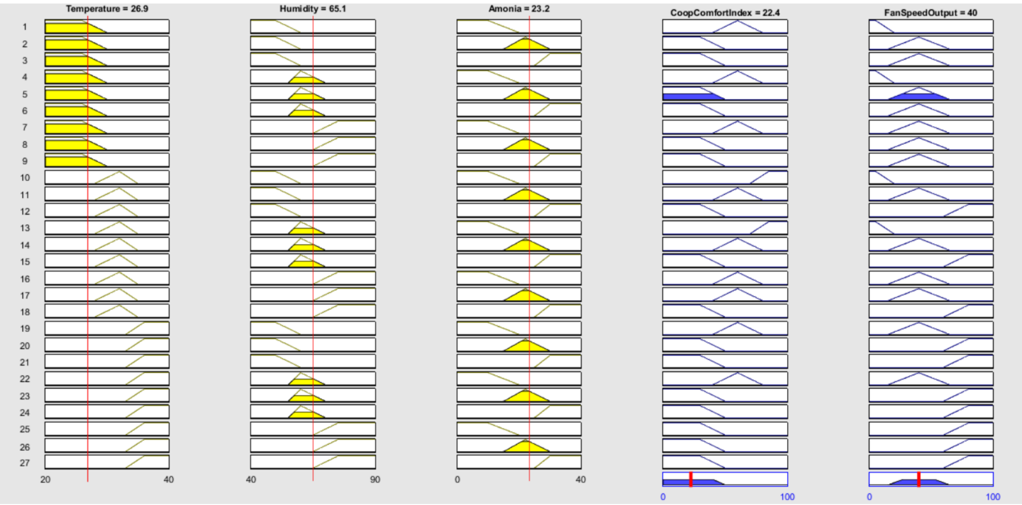


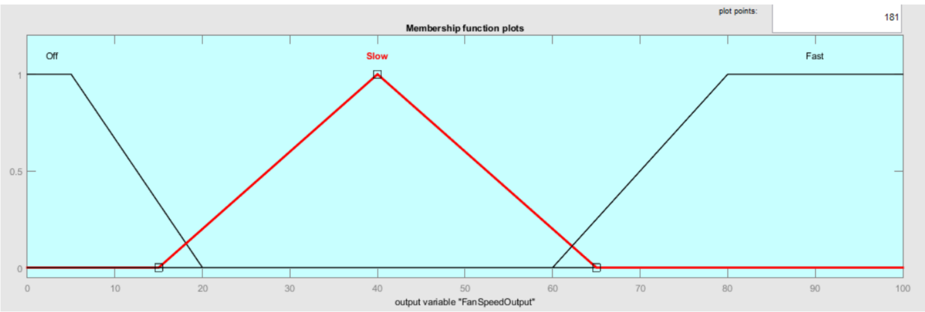
Figure 14. Visualization of Defuzzification and Curve Truncation for Coop Status Index Output in MATLAB

The visualization in Figure 14 illustrates the correlation between the linguistic rules and the final numerical output of 22.4 as projected by the MATLAB Fuzzy Logic Toolbox. The shaded area represents the aggregated result of the active fuzzy rules, specifically where the "Safe" and "Warning" membership functions overlap. The vertical line cutting through the shaded region identifies the Centroid, which serves as the system's final decision point. The truncation at the 0.49 level indicates that the current sensor inputs Temperature, Humidity, and Ammonia strongly trigger the conditions defined in the rule base, but not to the point of absolute saturation. The shift of the centroid toward the left side of the scale (the 20-30 range) visually confirms that despite slight fluctuations in the microclimate, the dominant environmental state remains firmly within the "Safe" category.

Furthermore, the slight discrepancy between this visual projection (22.4) and the manual integral calculation (22.62) is a result of the discretization method used by the software. MATLAB calculates the area by sampling thousands of discrete points across the curve, whereas the manual method utilizes continuous calculus. However, since the deviation remains remarkably low (0.97%), this visualization proves that the mathematical model is highly reliable for real-time monitoring of broiler coop conditions.

b. Defuzzification Analysis of the Fan Speed Output

The truncation of the Slow Fan set curve at the 0.49 ordinate dissects the geometric area into three specific sections LD with abscissa point boundaries situated at coordinates 27.25 and 52.75.



Gambar 1 Defuzzification Curve Graph for Fan Speed Output in MATLAB

1) Total Area Calculation (TLD)

- $LD_1 = Left\ Triangle$
- $LD_1 = \frac{(27{,}25 - 15) \times 0{,}49}{2} = 3,00125$
- $LD_{2'} = Middle\ Triangle$
- $LD_2 = 25,5 \times 0,49 = 12,495$
- $LD_3 = Right\ Triangle$
- $LD_3 = \frac{(65 - 52{,}75) \times 0{,}49}{2} = 3,00125$
- Total Area Calculation (TLD) = $LD_1 + LD_2 + LD_3 = 3,00125 + 12,495 + 3,00125 = 18,4975$

The TLD value of 18.4975 represents the total geometric magnitude of the fuzzy inference result. Physically, this value quantifies the "degree of activation" of the fan speed rules. A larger area indicates a strong and stable command signal, ensuring that the system provides a consistent response to environmental changes rather than reacting to minor sensor noise.

2) Static Moment Integral Calculation (M)

- $M1 = \int_{15}^{27{,}25} (0,04x - 0,6)x\,dx = \int_{15}^{27{,}25} \left(0,04x^2 - 0,6x\right)dx = 0,0133x^3 - 0,3\,x^2 |$
- $M2 = \int_{27{,}25}^{52{,}75} 0,49x\,dx = 0,245\,x^2 \Big|_{27{,}25}^{52{,}75} = 499,80$
- $M3 = \int_{52{,}75}^{65} (2,6 - 0,4x)x\,dx = \int_{52{,}75}^{65} \left(2,6x - 0,4x^2\right)dx = 1,3x^2 - 0,0133x^3 \Big|_{52,}^{65}$
- Total Moment (TM) = $66,35 + 499,80 + 173,75 = 739,90$

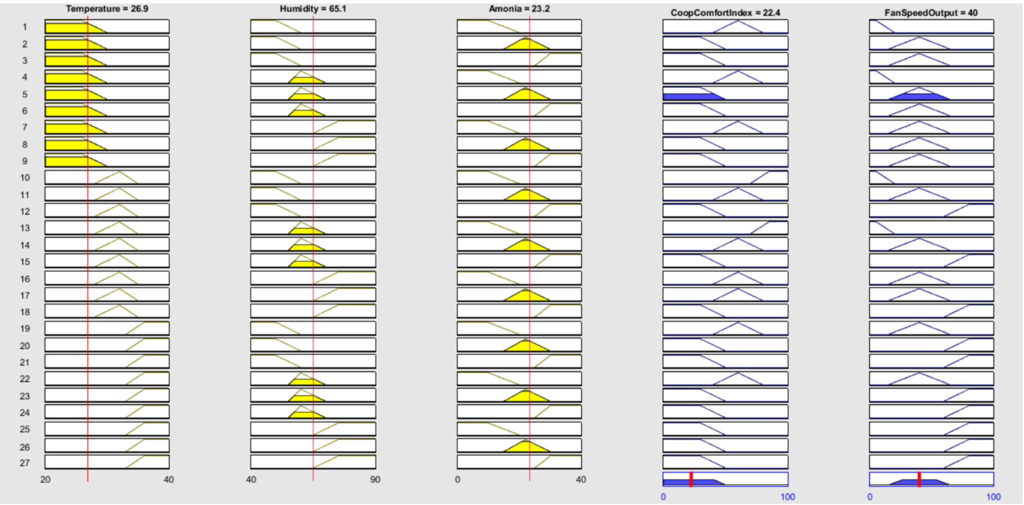
The Total Moment (TM) of 739.90 signifies the mathematical "leverage" or the distribution of the control weight along the speed domain. By using integration, we ensure that the non-linear characteristics of the fuzzy membership functions are captured accurately. This value acts as the weighted numerator that dictates exactly where the fan speed should settle to achieve optimal microclimate balance.

3) Final Value Affirmation (Crisp Output)

The center of mass point for the fan output area is extracted using the division ratio between the Total Moment (TM) and the Total Area (TLD):

$$Z^{*} = \frac{TM}{TLD} = \frac{739{,}90}{18{,}4975} = 40$$

The resulting crisp value of 40.00 is the definitive "Fan Speed Index." On a scale of 0 to 100, this value corresponds to a "Slow to Medium" actuation. Physically, this indicates that the fuzzy logic system has calculated a need for moderate air displacement. The microcontroller will convert this index into a PWM signal to drive the exhaust fan at 40% of its maximum capacity. This specific speed is sufficient to flush out stagnant air and ammonia without causing excessive airflow that could stress the poultry or waste electrical energy, thereby achieving a perfect balance between bird welfare and operational efficiency.



Gambar 2 Visualization of Defuzzification and Curve Truncation for Fan Speed Output in MATLAB

c. Computational Precision Comparison

The alignment results contrasting the analytical calculations derived via manual and theoretical integral computation against the commercial simulator calculations using MATLAB software are comprehensively encapsulated in Table 1.

Table 1. Comparison of Theoretical Mathematical Defuzzification against MATLAB Computational Simulation

Response Variable (Output)	**Mathematical Calculation (Manual)**	**Computational Simulation (MATLAB)**	**Percentage of Deviation (Error)**
Coop Status Index (%)	22,62	22,4	0,97%
Fan Speed (PWM)	40,00	40,00	0,00%

An objective assessment of the metrics presented in Table 1 definitively confirms that the mathematical architecture demonstrates a high level of precision. However, a slight deviation of 0.97% is observed in the Coop Status Index, whereas the Fan Speed variable shows a 0.00% error (perfect alignment). The deviation in the Coop Status Index .097% occurs due to the "Discretization" process in MATLAB's Fuzzy Logic Toolbox. While manual calculation uses continuous definite integrals to find the exact centroid, MATLAB approximates the area under the curve by dividing it into thousands of small discrete segments grids. This numerical approximation leads to a negligible floating-point difference when processing the specific Mamdani membership function area for the coop status.

Conversely, the Fan Speed shows 0.00% error because the resulting output area for this specific test case formed a perfectly symmetrical geometric shape. In such cases, the centroid (Z*) falls exactly on a single integer point, allowing both the manual integral and the MATLAB numerical solver to arrive at the same absolute value of 40.00.The overall error rate, which remains significantly below the 1% threshold, securely legitimizes that the construction of the Mamdani Fuzzy membership functions is exceptionally logical, solid, and optimally calibrated (Gunadi et al., 2021).

d. Validation of Microcontroller Hardware Implementation

To empirically substantiate that the validated fuzzy logic architecture has been successfully translated into C++ programming syntax and operates seamlessly within the embedded system, real-time computational testing was conducted via the microcontroller's serial interface. The input parameters identical to the previous simulation Temperature 26.90°C, Humidity 65.10%, and Ammonia 23.24 ppm were injected into the hardware processing unit.

```
===== MONITORING =====
Suhu: 26.90
Kelembapan: 65.10
Amonia(ppm): 23.24
Kipas: PELAN
Heater: TERANG
Status Kandang: BURUK
======================
```

Figure 15. Real-Time Computational Output via Microcontroller Serial Monitor

The actual reading obtained from the serial monitor interface Figure 15 prominently indicates that the execution of the fuzzy algorithm at the hardware level produces an identical actuation output Fan Speed: 22.60 and Coop Status: 40.00. This empirical evidence solidifies the conclusion that the developed IoT-based microclimate monitoring prototype functions with supreme consistency, bridging the gap between theoretical modeling, software simulation, and actual hardware deployment without any computational degradation.

CONCLUSION

Based on the computational analysis and the architectural design of the Mamdani Fuzzy logic system for determining broiler coop conditions, it can be concluded that this methodology is highly effective in processing multi-variable environmental data. The constructed system, which integrates three predictor parameters (Temperature, Humidity, and Ammonia) alongside a comprehensive 27-rule base matrix, is capable of delivering precise actuation decisions regarding Fan Speed and Coop Comfort Status.

The system validation, conducted by comparing theoretical mathematical calculations utilizing the Center of Gravity (COG) defuzzification method against MATLAB software simulations, demonstrated a high degree of accuracy. The analytical manual computation yielded a value of 22.62, while the computational simulator recorded 22.4, resulting in a minimal deviation error rate of 0.97%. This low margin of error proves that the formulated fuzzy logic architecture operates with optimal precision and reliability. Consequently, this computational blueprint is fully prepared to be embedded into C++ programming environments on microcontrollers, such as the ESP32, facilitating a real-time, smart monitoring and control system based on Internet of Things (IoT) technology.

Building upon the findings of this study, several avenues for future research are proposed. First, the integration of Machine Learning algorithms, such as Artificial Neural Networks (ANN), could be explored to enhance the system's predictive capabilities regarding potential microclimate fluctuations before they occur. Second, the implementation of Edge Computing could be investigated to reduce data latency in large-scale poultry farms. Lastly, future studies should consider the incorporation of energy-efficiency metrics to analyze the long-term operational cost savings achieved by this fuzzy-based automation compared to conventional manual management systems.

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