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# Design of Temperature and Humidity Control System for Cocoa Bean Dryers Using the Fuzzy Mamdani Method

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**Abstract**

This research aims to develop a fuzzy logic control system for optimizing temperature and humidity during cocoa bean fermentation. The study employs a literature review method and data analysis using MATLAB. A Mamdani-type fuzzy inference system is designed to control the temperature and humidity of a cocoa bean dryer. Input variables include temperature (0-65°C) and humidity (0-100%), while output variables are heater and fan settings. The system's performance is evaluated using a case study, demonstrating its ability to adjust heater and fan operations based on environmental conditions. Results show that for an input of 65°C temperature and 50% humidity, the system recommends turning off the heater (membership value 79.8) and running the fan at high speed (membership value 84.7). This fuzzy logic approach offers a promising solution for maintaining optimal conditions during cocoa bean fermentation, potentially improving the quality and consistency of the final product.

**Keywords:** cocoa fermentation, fuzzy logic control, temperature regulation

## INTRODUCTION

Cocoa (Theobroma cacao L.) is an important plantation commodity in Indonesia, supplying about 15% of the world's cocoa beans and ranking third after Côte d'Ivoire and Ghana. However, in 2018, Indonesia dropped to sixth place due to a decline in production (Ariningsih *et al.* 2021). Despite high production volumes, the quality of Indonesian cocoa beans remains low, mainly due to suboptimal post-harvest processing and a lack of fermentation (Gonibala *et al.* 2018). Cocoa fermentation helps break down the pulp layer and deactivate the cotyledons. Cocoa fermentation helps to break down the pulp layer and deactivate the cotyledons. The biochemical reactions within the beans naturally change, reducing the bitterness and astringency of the cocoa. (Tarigan and Iflah 2017). Fermentation of cocoa beans is crucial in developing the chocolate flavor, changing the seed color from purple to brown, and reducing bitterness, which results in beans with better quality and aroma (Hartuti *et al*. 2018).

Cocoa bean fermentation not only enhances flavor quality but also triggers biochemical changes that enrich the aroma (Sigalingging *et al*. 2020). Inadequate fermentation results in weak flavor, and chocolate aroma does not develop in unfermented beans (Gonibala *et al*. 2018). The success of fermentation is influenced by several factors, such as temperature, stirring method, and the amount of cocoa beans being fermented (Hartuti *et al*. 2021). Uncontrolled temperature in the fermentation space can negatively affect bean quality, highlighting the need for a control system to regulate optimal temperature and humidity (Hartuti *et al.* 2021). By using fuzzy rules, this system is able to optimize the fermentation process, thereby ensuring that the quality of the cocoa beans produced remains consistent and optimal (Putra *et al*. 2022). In addition, this flexible control can also reduce the risk of damage due to temperature fluctuations, making it an effective tool in increasing the yield of fermented cocoa beans.

The Mamdani fuzzy logic control system is an effective method for handling uncertainties in cocoa bean drying, adopting human reasoning through understandable linguistic rules (Suteja and Suastika 2020). This method works by converting inputs into fuzzy values and processing them through a fuzzy rule base (Safitri *et al.* 2023). The purpose of implementing fuzzy logic is to automatically achieve optimal drying conditions, adjusting temperature and humidity based on actual conditions and maintaining quality consistency (Rahman and Putra 2021). The implementation of the Mamdani fuzzy logic system has been shown to increase energy efficiency by up to 25% and produce cocoa beans with higher uniformity compared to conventional methods (Widodo *et al.* 2018). Using a knowledge-based approach, this system can quickly adjust drying parameters to produce a high-quality final product, even in dynamic situations (Setiawan *et al.* 2022).

## METHODS

The method used in writing this article is a literature review and data analysis using MATLAB (Matrix Laboratory). The literature review involves a series of activities related to searching, collecting, and selecting data from various sources, such as books, articles, journals, and other publications related to the research topic, to produce a paper on a single topic (Marzali 2016). MATLAB, short for "Matrix Laboratory," is an advanced programming software that can be used to solve various problems, including data analysis, algorithm development, simulation, visualization, and decision-making (Nasution and Yahfizham 2024).

### Literature Review Method

The first stage in writing this article was conducted using the literature review method, which involves searching for relevant information from various sources related to the fuzzy logic control system, particularly in terms of regulating temperature and humidity in cocoa bean drying equipment. The literature review is a research process that includes reviewing various books, scientific journals, and other publications related to the research topic (Cahyono *et al.* 2019). The purpose of this review is to build a strong knowledge foundation and gain a deep understanding of concepts and issues related to the researched topic (Subhan *et al.* 2021). Literature reviews serve several functions. They allow us to identify other studies relevant to our topic, understand the trajectory of previous research, and generate new ideas that could offer solutions to problems found in earlier studies (Snyder 2019).

### Matrix Laboratory data analysis

In data analysis using MATLAB (Matrix Laboratory), a fuzzy logic approach is applied to control the temperature and humidity of a cocoa bean drying machine using the Mamdani method. The Mamdani method is known as one of the most widely used fuzzy inference methods due to its intuitive approach and its ability to handle linguistic variables (Sihombing 2024). In the Mamdani method, both input and output variables are divided into one or more fuzzy sets (Rindengan and Langi 2019).

The process begins by defining membership functions for each input variable, using a trapezoidal shape in this study to represent uncertainty (Darmawati 2017). This membership function is defined through four main parameters that control the sloping and flat parts of the trapezoidal curve. Then, fuzzy rules are created based on "IF-THEN" logic, using the AND operator to link inputs with outputs (Hamala 2023). The next step is rule composition using the min-max method to derive fuzzy conclusions. The final stage is defuzzification, which is the process of obtaining a crisp value from the fuzzy set.

### Determining Input and Output Variables

Determining input and output variables is known as the fuzzification stage, namely the process of changing logical input into a fuzzy set or translating the output in fuzzy form (Fatkhurrozi and Setiawan 2024). The temperature signal as input is a crisp value ranging from 0 to 65. Data is obtained from readings of the DHT 22 sensor within a temperature range of 0°C - 65°C. These fixed values are converted into fuzzy input sets, namely Normal, Warm, Optimal, and Hot.

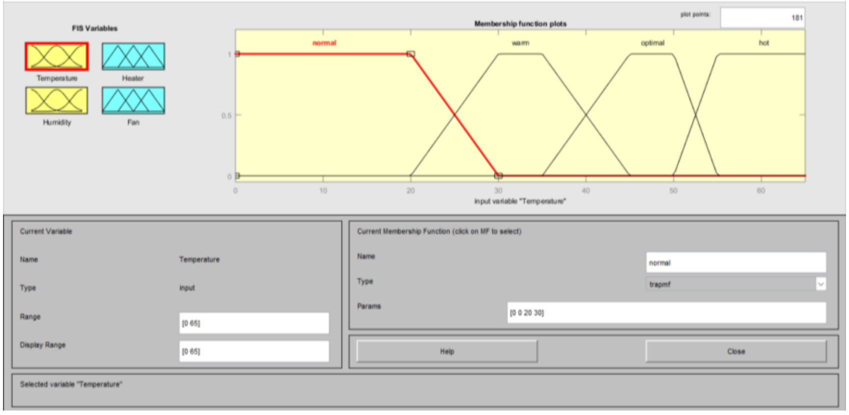


Figure 1. Input Variable Temperature for Normal Set

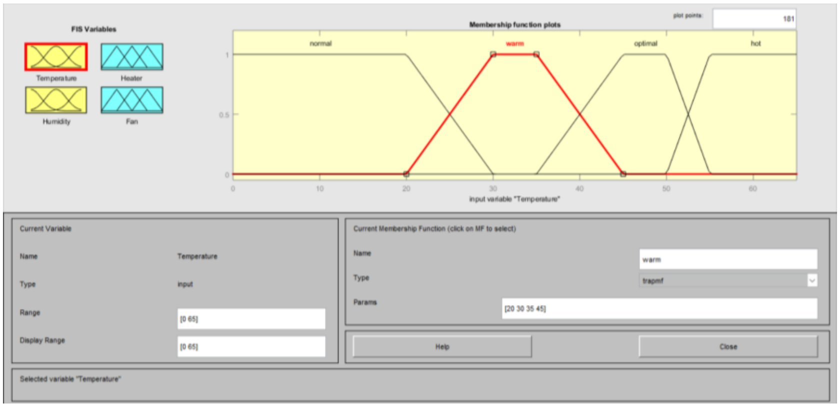


Figure 2. Input Variable Temperature for Warm Set


Figure 3. Input Variable Temperature for Optimal Set

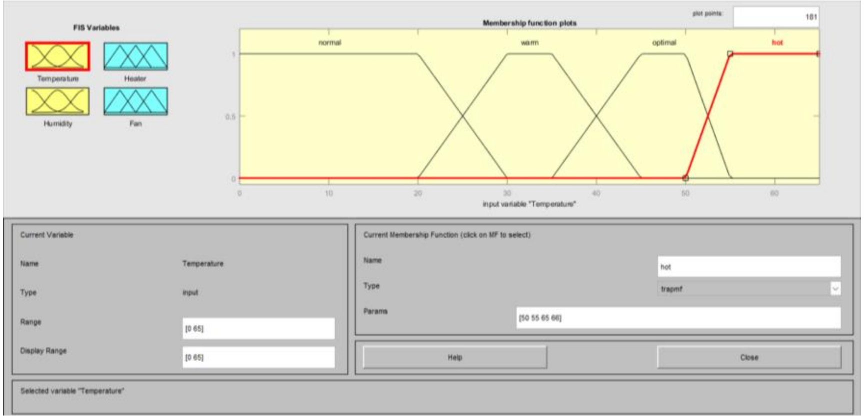

Figure 4. Input Variable Temperature for Hot Set

The humidity signal as input consists of crisp values ranging from 0 to 100. This data is obtained from readings of the DHT 22 sensor within a range of 0 to 100%. These crisp values are then transformed into fuzzy input set groups, namely Dry, Humid, and Wet.

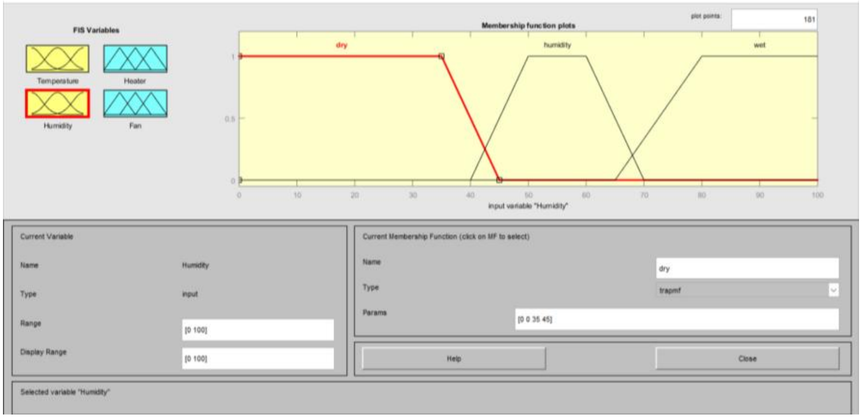

Figure 5. Input Variable Humidity for Dry Set

Figure 6. Input Variable Humidity for Humid Set

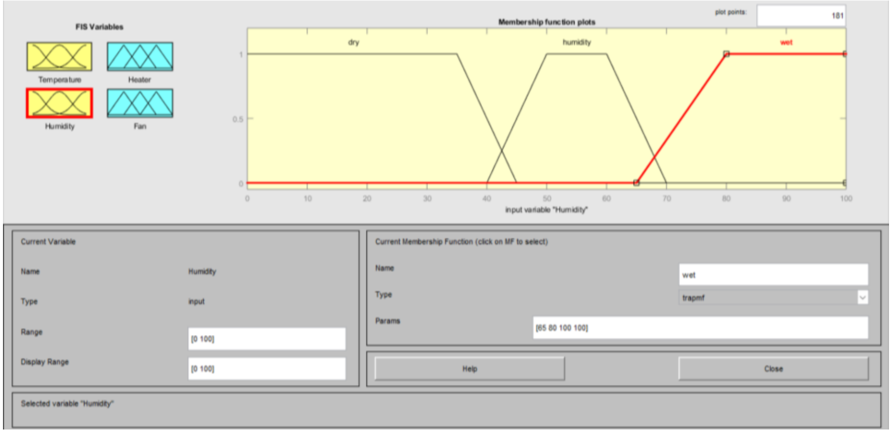

Figure 7. Input Variable Humidity for Wet Set

The heater signal as an output is a crisp value ranging from 0° to 100°. This crisp value is then transformed into fuzzy output sets of On and Off.

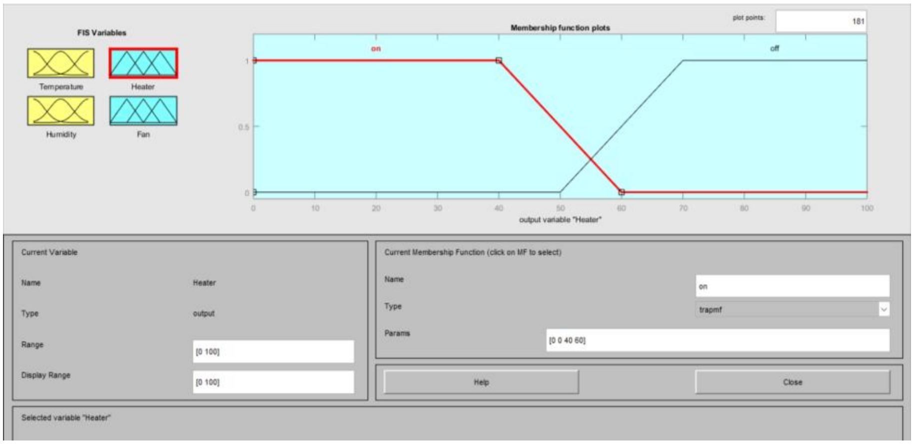

Figure 8. Output Variable Heater for On Set

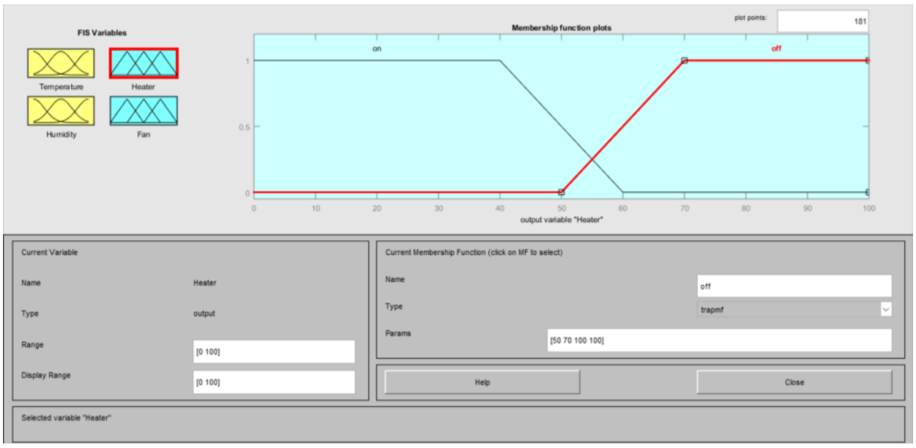

Figure 9. Output Variable Heater for Off Set

The output signal from the fan is represented as a definite number ranging from 0 to 100. This number is obtained based on the temperature range of the heater, which is between 0°C and 100°C. Subsequently, this definite number is classified into several groups for the fan output, namely Off, Normal, and Fast.

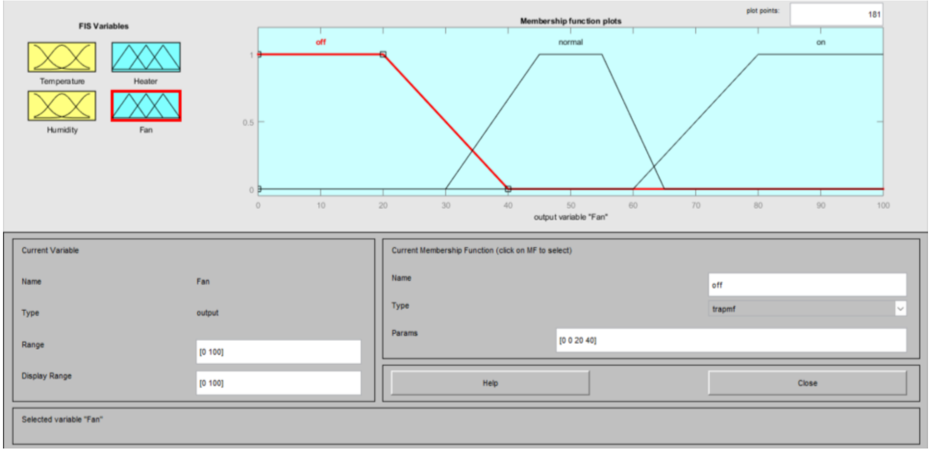

Figure 10. Output Variable Fan for Off Set

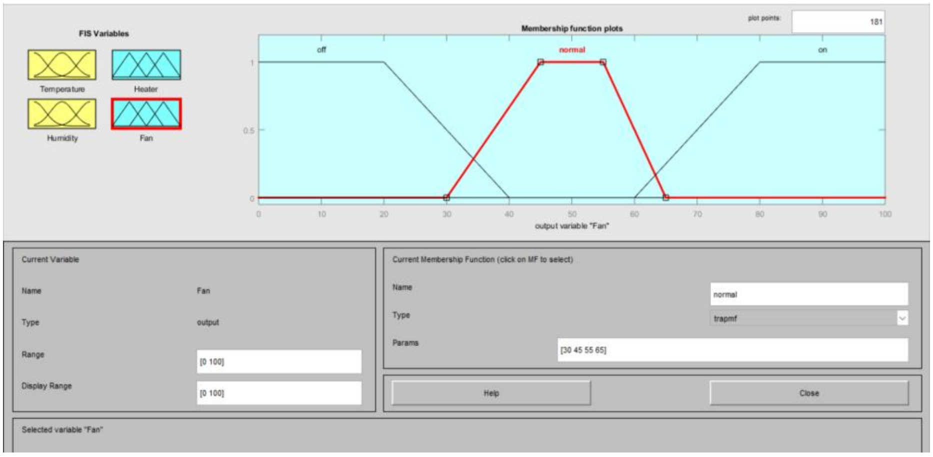

Figure 11. Output Variable Fan for Normal Set

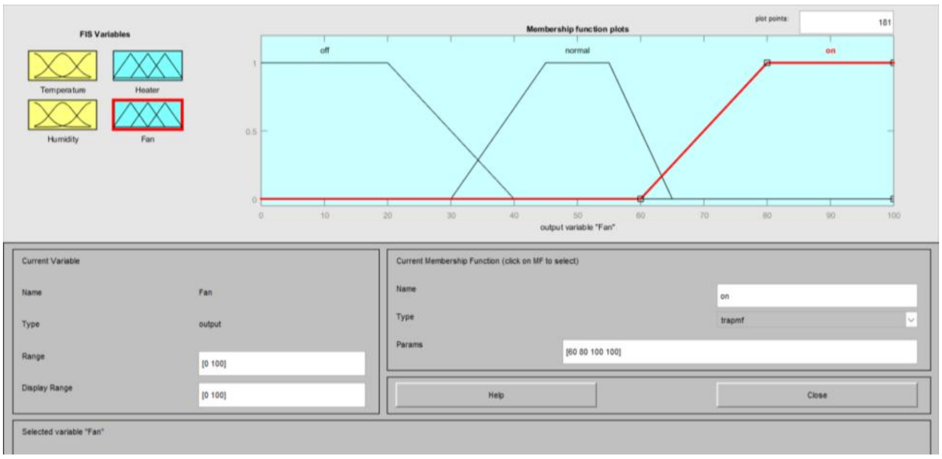

Figure 12. Output Variable Fan for Fast Set

## RESULTS AND DISCUSSION

This research employs a fuzzy logic approach to regulate temperature and humidity in cocoa bean drying equipment using the Mamdani method. In determining the temperature and humidity ranges for the cocoa bean drying device, literature data sources that have been developed and modified were used. The literature review conducted bases the optimization decisions for temperature and humidity of the dryer on cocoa bean products using heaters and fans, with attention to final product quality. Fuzzy Logic Controller (FLC) is a control system application that applies fuzzy logic principles (Muchtar and Syamsur 2021). The following is an analysis using the Fuzzy Logic Control (FLC) method. The fuzzy system design steps consist of 5 stages:

1. **Identification of fuzzy input and output variables**

In this fuzzy method, there are input variables used to define environmental conditions with various ranges of values, which can then be used to establish fuzzy rules in the decision-making system (Kastina and Silalahi 2016).

Table 1. Temperature and Humidity Input Variables in Fuzzy Method

| **Variabel Input** | **Fuzzy Parameter** | **Range** | |
|---|---|---|---|
| | | **Min.** | **Max.** |
| Temperature | Low | 0°C | 30°C |
| | Medium | 30°C | 60°C |
| | High | 55°C | 100°C |
| Humidity | Low | 0% | 40% |
| | Medium | 30% | 60% |
| | High | 55% | 100% |

Source: Ramadhani *et al*. 2023

Table 2. Temperature and Humidity Output Variables in Fuzzy Method

| Variabel Input | Fuzzy Parameter | Range | |
|---|---|---|---|
| | | Min. | Max. |
| Temperature | Low | 0°C | 40°C |
| | Medium | 30°C | 70°C |
| | High | 60°C | 100°C |
| Humidity | Low | 0 | 20 |
| | Medium | 15 | 50 |
| | High | 40 | 100 |

Source: Ramadhani *et al*. 2023

**2. Fuzzification**

Fuzzification calculation:

A. Temperature 55°C:
- Medium Temperature (30°C - 60°C): $\mu\_medium(55) = (60 - 55) / (60 - 30) = 0.167$
- High Temperature (55°C - 100°C): $\mu\_high(55) = (55 - 50) / (60 - 50) = 0.5$

B. Humidity 35%:
- Low Humidity (0% - 40%): $\mu\_low(35) = (40 - 35) / (40 - 0) = 0.125$
- Medium Humidity (30% - 60%): $\mu\_medium(35) = (35 - 30) / (60 - 30) = 0.167$

This fuzzification can evaluate temperature and humidity in several fuzzy categories to determine the drying conditions for cocoa beans. The results of this fuzzification will be used in the next step, which is the application of fuzzy rules to determine the appropriate actions in the drying process (Tamaji and Utama. 2023). Based on the fuzzification calculations, it can be determined that a temperature of 55°C has a membership degree of 0.167 in the medium temperature category and a membership degree of 0.5 in the high temperature category. Meanwhile, the humidity variable can have a membership degree of 0.125 in the low humidity category and a membership degree of 0.167 in the medium humidity category. Fuzzification will ensure that the input values are in a form that is understandable by the fuzzy rules, allowing the system to work with uncertain data (Yunus 2018).

**3. Fuzzy Rules**

The fuzzy rules created will use fuzzification data to determine the output produced. Fuzzification is the process of transforming crisp values into fuzzy values (Nugroho *et al*. 2019). In this rule, the input variables generated through the fuzzification process will be used to evaluate conditions and produce outputs that align with the desired conditions. Fuzzification and fuzzy rules will work together in the fuzzy logic system to handle uncertainty and complexity in decision-making (Suherman and Widyaningrum 2024).

Table 3. Fuzzy Rules Used to Determine The Conditions of The Cocoa Bean Dryer

| **Rule-** | **Temperature** | **Humidity** | ***Heater*** | ***Fan*** |
|---|---|---|---|---|
| 1 | Normal | Dry | Off | Off |
| 2 | Normal | Humid | On | Off |
| 3 | Normal | Wet | On | Off |
| 4 | Warm | Dry | Off | Off |
| 5 | Warm | Humid | On | Off |
| 6 | Warm | Wet | On | Off |
| 7 | Optimal | Dry | Off | Off |
| 8 | Optimal | Humid | On | Normal |
| 9 | Optimal | Wet | On | Normal |
| 10 | Hot | Dry | Off | Off |
| 11 | Hot | Humid | Off | On |
| 12 | Hot | Wet | Off | On |

For the two input variables and two output variables, the rule arrangement used is IF temperature (...) AND humidity (...) THEN heater (...) fan (...).

Table 4. Input and Domain

| **Input** | **Member Set** | **Domain** |
|---|---|---|
| Temperature | Normal | [0 0 20 30] |
| | Warm | [20 30 35 45] |
| | Optimal | - |
| | Hot | [50 55 65 66] |
| Humidity | Dry | [0 0 35 45] |
| | Humid | [40 50 60 70] |
| | Wet | [65 80 100 100] |

1. Input "Temperature"
    - Membership Function (Normal)

      $F(X) = \{0, x \leq 0; \frac{x-0}{0-0}, 0 \leq x \leq 0; 1, 0 \leq x \leq 20; \frac{75-x}{75-73}, 20 \leq x \leq 30; 0, x$

$\leq 30\}$

- Membership Function (Warm)

  F(X) = {0, x $\leq 20; \frac{x-20}{30-20}$ , $20 \leq x \leq 30$; 1, $30 \leq x \leq 35; \frac{45-x}{45-35}$, $35 \leq x \leq 45$; 0, x $\leq 45\}$

- Membership Function (Hot)

  F(X) = {0, x $\leq 50; \frac{x-50}{55-50}$ , $50 \leq x \leq 55$; 1, $55 \leq x \leq 65; \frac{65-x}{66-65}$, $65 \leq x \leq 66$; 0, x $\leq 66\}$

2. Input “Humidity”

- Membership Function (Dry)

  F(X) = {0, x $\leq 0; \frac{x-0}{0-0}$ , $0 \leq x \leq 0$; 1, $0 \leq x \leq 35; \frac{45-x}{45-35}$, $35 \leq x \leq 45$; 0, x $\leq 45\}$

- Membership Function (Humid)

  F(X) = {0, x $\leq 40; \frac{x-40}{50-40}$ , $40 \leq x \leq 50$; 1, $50 \leq x \leq 60; \frac{70-x}{70-60}$, $60 \leq x \leq 70$; 0, x $\leq 70\}$

- Membership Function (Wet)

  F(X) = {0, x $\leq 65; \frac{x-65}{80-65}$ , $65 \leq x \leq 80$; 1, $80 \leq x \leq 100; \frac{100-x}{100-100}$, $100 \leq x \leq 100$; 0, x $\leq 100\}$

Table 5. Output and Domain

| Output | Member Set | Domain |
|---|---|---|
| Heater | On | [0 0 40 60] |
| | Off | [50 70 100 100] |
| Fan | Off | [0 0 20 40] |
| | Normal | [30 45 55 65] |
| | Fast | [60 80 100 100] |

1. Output “Heater”

- Membership Function (On)

  F(X) = {0, x $\leq 0; \frac{x-0}{0-0}$ , $0 \leq x \leq 0$; 1, $0 \leq x \leq 40; \frac{60-x}{60-40}$, $40 \leq x \leq 60$; 0, x $\leq 60\}$

- Membership Function (Off)

  F(X) = {0, x $\leq 50; \frac{x-50}{70-50}$ , $50 \leq x \leq 70$; 1, $70 \leq x \leq 100; \frac{100-x}{100-100}$, $100 \leq x \leq 100$; 0, x $\leq 100\}$

2. Output “Fan”

- Membership Function (Off)

  F(X) = {0, x $\leq 0; \frac{x-0}{0-0}$ , $0 \leq x \leq 0$; 1, $0 \leq x \leq 20; \frac{40-x}{40-20}$, $20 \leq x \leq 40$; 0, $x \leq 40\}$

- Membership Function (Normal)

$F(X) = \{0, x \leq 30; \frac{x-30}{45-30}, 30 \leq x \leq 45; 1, 45 \leq x \leq 55; \frac{65-x}{65-55}, 55 \leq x \leq 65; 0, x \leq 65\}$

- Membership Function (Fast)

  $F(X) = \{0, x \leq 60; \frac{x-60}{80-60}, 60 \leq x \leq 80; 1, 80 \leq x \leq 100; \frac{100-x}{100-100}, 100 \leq x \leq 100; 0, x \leq 100\}$

**4. Inferensi Fuzzy**

The fuzzy inference indicates that the degree of membership needs to be calculated for each rule. This fuzzy inference process involves combining the membership values from the inputs with the fuzzy rules to determine the appropriate output (Basra and Permana 2023).

Calculate membership degrees for each rule:

- Rule 1: Medium temperature (0.167) and low humidity (0.125) → minimum value = 0.125 (Heater: High, Fan: Low)
- Rule 2: Medium temperature (0.167) and medium humidity (0.167) → minimum value = 0.167 (Heater: Medium, Fan: Medium)
- Rule 3: High temperature (0.5) and low humidity (0.125) → minimum value = 0.125 (Heater: High, Fan: Medium)
- Rule 4: High temperature (0.5) and medium humidity (0.167) → minimum value = 0.167 (Heater: High, Fan: High)

**5. Defuzzifikasi**

The final step is defuzzification, which is a crucial stage in fuzzy logic where the results from applying various fuzzy rules are combined and transformed. This process takes the fuzzy sets formed from the combination of several fuzzy rules and converts them into a aguspecific numerical value. This final value falls within the previously determined fuzzy set domain range (Suprianto and Agustin 2022). Defuzzification serves as validation that previous calculations align with expected results.

**Defuzzification Using Integration**

1) Heater Defuzzifikasi :

   Fuzzy values for Heater:

- High: 0.125 dari rule 1, 0.125 from rule 3, and 0.167 from rule 4.
- Medium: 0.167 from rule 2.

  COG calculation for Heater:

  $$\text{Output Heater} = (\int (0.125 \times 100) + (0.167 \times 70) + (0.167 \times 100)\, dx) / (\int 0.125 + 0.167 + 0.125 + 0.167\, dx) = \mathbf{79.8}$$

2) Fan Defuzzifikasi:

   Fuzzy values for Fan:

- Low: 0.125 from rule 1.
- Medium: 0.167 from rule 2, 0.125 from rule 3
- High: 0.167 from rule 4.

  COG calculation for Fan:

  $$\text{Output Fan} = (\int (0.125 \times 20) + (0.167 \times 50) + (0.125 \times 50) + (0.167 \times 100)\, dx) / (\int 0.125 + 0.167 + 0.125 + 0.167\, dx) = \mathbf{15.3}$$

This integral method produces the average center of gravity value from the fuzzy set output. Based on the calculations performed, its compatibility with the MatLab system can be determined through the rule viewer on the system design below.

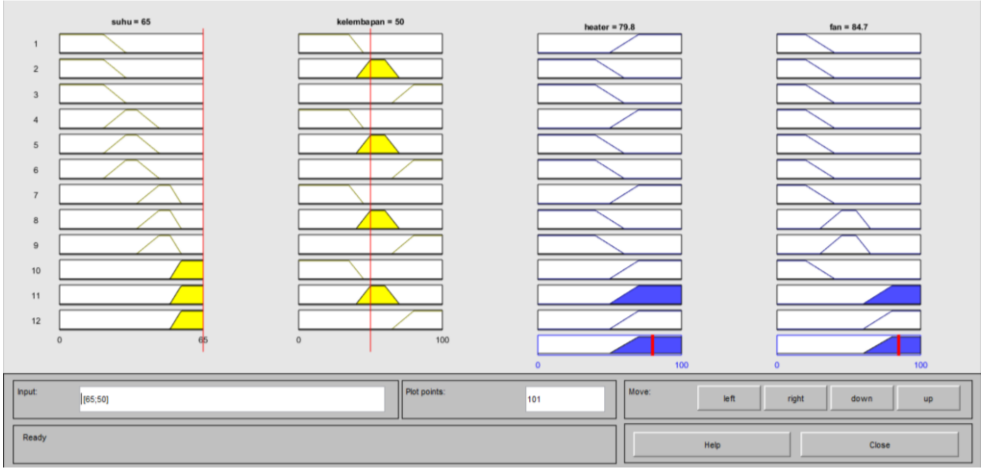


Figure 13.  Shows The Fuzzy Rule Conditions in MATLAB

Figure 1 The experiment was conducted with an input temperature value of 65°C belonging to the hot set and humidity of 50% belonging to the humid set. The output obtained shows a heater membership value of 79.8, indicating the OFF set, and the fan output obtains a membership value of 84.7, indicating the FAST set.

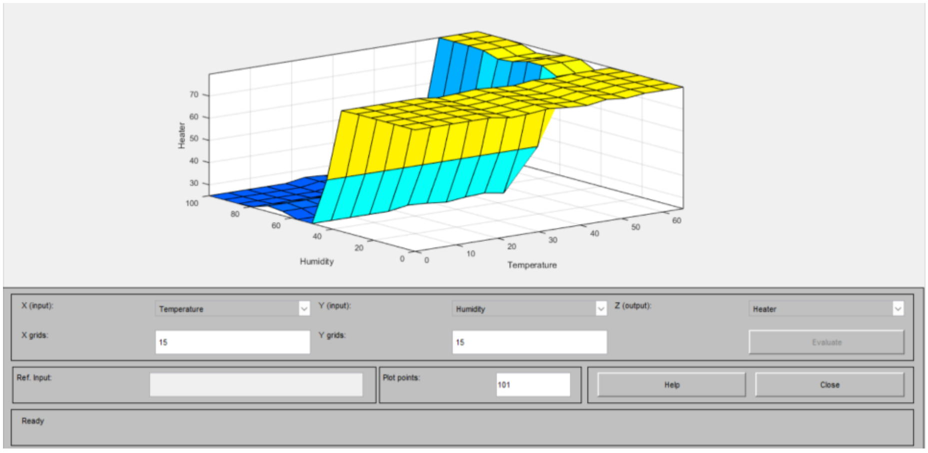


Figure 14. Surface viewer

The surface viewer serves as a visualization tool that allows users to see the relationship between input and output variables in the fuzzy system (Rohmad *et al.* 2015). Based on Figure 14, it can be seen that the x and y axes represent temperature and humidity, respectively, while the z axis represents the output, which is the heater.

## CONCLUSION

Based on the results and discussion section, This study successfully demonstrated the implementation of a Mamdani-type fuzzy logic control system for optimizing cocoa bean drying conditions. Through MATLAB simulation with specified input variables of temperature (0-65°C) and humidity (0-100%), the system effectively determined appropriate heater and fan settings. The case study validation showed that at 65°C temperature and 50% humidity, the system intelligently recommended turning off the heater (membership value 79.8) and operating the fan at high speed (membership value 84.7), demonstrating its capability to maintain optimal drying conditions. The developed fuzzy logic system, with its comprehensive rule base and carefully defined membership functions, offers a promising automated solution for maintaining consistent cocoa bean quality during the drying process. This implementation suggests potential improvements in energy efficiency and product quality consistency compared to conventional drying methods, though further practical validation would be valuable for industrial applications.

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