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Fuzzy Logic Approach in Palm Oil Production Using the Mamdani Method

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Abstract

This research investigates the application of the Mamdani fuzzy logic method for predicting palm oil production based on consumer demand and supply data. The purpose is to enhance the accuracy of production forecasts critical for optimizing the palm oil industry in Indonesia. The methodology involves data collection on consumer demand and supply, formation of fuzzy sets, rule definition, and inference processing. Results indicate that the Mamdani method effectively correlates demand and supply levels with production outcomes, yielding consistent predictions when compared to manual calculations. The findings conclude that implementing fuzzy logic can significantly improve decision-making in palm oil production, leading to more efficient and sustainable practices within the industry. This study highlights the potential of fuzzy logic applications in agricultural production systems for better resource management.

Keywords: Fuzzy Logic, Palm Oil Production, Mamdani Method

INTRODUCTION

Production is an activity performed to add value to an object, making it more useful for meeting the needs of many people. In large companies, the production process is always a key focus, as the main factor for entrepreneurs in determining the quality of the produced products comes from the production process. The production of palm oil is the result of processing oil palm fruit, which can be converted into various types of food. Palm oil has advantages over other vegetable oils, such as coconut, soybean, or sunflower oil. The advantages of palm oil in terms of its production include high yield, long economic lifespan, low risk, sufficient supply, and diverse uses (Arsyad & Maryam, 2017). After assessing the quality of the production, the next step is to estimate future production based on the factors influencing the production process (Tundo 2020). This research discusses palm oil production influenced by consumer demand and the available palm oil supply measured in tons. Palm oil is a significant plantation commodity that plays an essential role in Indonesia's economy. The production of palm oil in Indonesia has been continuously increasing (Ikromina and Ujianto 2019). According to statistical data, Indonesia's estimated palm oil production in 2017 reached 35.359.384 tons. Conventional statistical approaches can make it more difficult for producers to determine production volume compared to rule-based statistical approaches (Verdian 2017). Palm oil plantations are highly profitable for the industry, leading to the conversion of many forests into palm oil plantations. Indonesia is the largest palm oil producer in the world, with plantations spread across various regions, including Sumatra, Java, Kalimantan, and Sulawesi. Timely and adequate palm oil production is a priority for palm oil companies (Maibang and Husein 2019).

One method that can be used to predict palm oil production is the application of fuzzy logic, as there are several data points that can be utilized in calculations to obtain production forecasts. In fuzzy logic calculations, there are several methods, including the Tsukamoto, Mamdani, and Sugeno methods. Each of these methods has distinct calculation approaches and results (Sukandy et al. 2014). In this case, the issue is how to apply the Mamdani fuzzy method to predict palm oil production based on stock data and demand levels. Fuzzy logic is chosen because its concept is easy to understand, highly flexible, tolerant of imprecise data, capable of modeling very complex nonlinear functions, able to integrate the experiences of experts directly without requiring training, compatible with conventional control techniques, and based on natural language (Susetyo et al. 2020).

METHODS

The research method used in this study is supported by the work of Wardani et al. (2017) and Simanjuntak and Fauzi (2023), which includes several steps. Figure 1 illustrates the flow of the stages from the beginning to the end of this research.

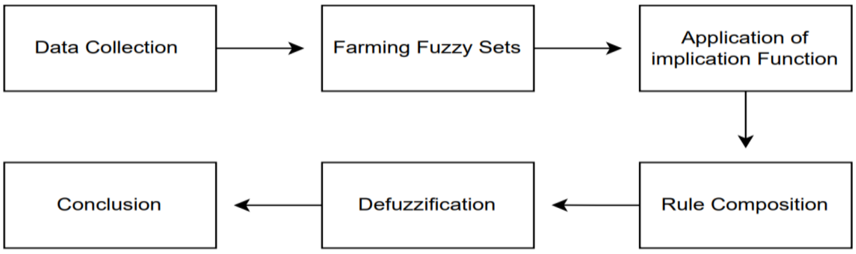

Figure 1. Research Flow

1. Data collection was conducted to obtain the necessary information for analyzing the application of fuzzy logic to palm oil production. The data used includes consumer demand and palm oil supply figures.
2. Fuzzy sets are formed by elements that create one or more fuzzy sets, such as input and output variables defined by the researcher based on the maximum, minimum, and median values of palm oil data.
3. In the Mamdani method, the implication function used is the minimum value between the two existing implications, commonly referred to as the α-predicate.
4. The rule composition helps identify the relationship between input conditions and the expected outcomes. The inference process is then used to combine all relevant rules and generate fuzzy output based on the degree of membership of the inputs. After inference, the next step is defuzzification, which converts the fuzzy output into a crisp value that can be applied in practice.
5. Defuzzification (manual and MATLAB) is the process of converting fuzzy output into a crisp value that can be applied. It often uses the centroid method, which calculates the center of the area under the membership function curve. Manually, this involves determining the fuzzy sets, calculating the area under the curve, and applying the centroid formula to obtain the crisp value. MATLAB is software for numerical analysis and computation that functions as an advanced mathematical programming language (Tjolleng 2017). In MATLAB, you can define membership functions and use fuzzy functions to automatically compute the crisp value. This process is essential for converting fuzzy information into measurable decisions that can be implemented in practice.
6. In conclusion, accurate data collection, such as demand and supply, is essential for analyzing the application of fuzzy logic in palm oil production. Fuzzy sets are formed based on the maximum, minimum, and median values of the data. The Mamdani method

employs implication functions using the minimum value to connect input and output. The inference process produces fuzzy output, which is then converted into a crisp value through defuzzification, either manually or using MATLAB. This process enables the conversion of fuzzy information into measurable and applicable decisions, enhancing the efficiency and accuracy of production.

RESULTS AND DISCUSSION

1. Data Collection & Fuzzy Sets

In this study, it is influenced by the values of input and output variables. The values of input and output variables are used to create the fuzzy membership functions for demand, supply, and production (Gushelmi 2018). The input of the defuzzification process is a fuzzy set derived from the composition of fuzzy rules, while the output generated is a number in the fuzzy set domain. Fuzzy sets will represent a condition or state in a variable fuzzy. Fuzzy sets have elements that have different degrees of membership (Basriati et al. 2020). The values of the input and output variables in this study can be determined based on the maximum, minimum, and median values of the palm oil data. The values of the input and output variables can be seen in the two tables below:

Table 1. Variabel Input (ton)

Variable Input (ton)	
Fuzzy Parameter	**Numerik**
Low Demand	1.601
Medium Demand	3.685
High Demand	6.826
Low Stock	368
Medium Stock	972
High Stock	3.127

Source: (Wardani et al., 2017)

The values of input variables in this study are divided into two types: demand and supply. In the demand for palm oil, there are three categories: low demand of 1,601 tons, medium demand of 3,685 tons, and high demand of 6,826 tons. The increasing output from palm oil processing has led to a rise in the demand for palm oil. The market share of palm oil is also promising because the demand for palm oil has shown a significant increase each year (Rahayu et al. 2018). In addition to demand, the values of input variables are also influenced by supply. The supply values in this study are categorized into three levels: low supply of 368 tons, medium supply of 972 tons, and high supply of 3,127 tons. Adequate raw material supply is crucial for ensuring smooth production processes. A smooth production process significantly impacts the sales levels and profits obtained by the company. Furthermore, having sufficient supply prevents production delays caused by a shortage of raw materials (Sofyan 2017).

Table 2. Variabel Output (ton)

Variable Output (ton)	
Fuzzy Parameter	**Numerik**
Low Production	1.817
Medium Production	3.811
High Production	6.454

Source: (Wardani et al., 2017)

The values of output variables in this study are divided into three categories: low production of 1,817 tons, medium production of 3,811 tons, and high production of 6,454 tons. Palm oil production is influenced by several factors, including land area, labor, and the number of factories. The area of agricultural land is a determining factor for the impact of agricultural commodities. The larger the area planted with palm oil, the greater the production generated by that land (Juliyanti & Usman 2018). Additionally, the more labor used, the greater the amount of palm oil produced. This aligns with research by Rafidah et al. (2022), which states that trained labor is one of the most important resources for increasing agricultural production. The amount of labor used will facilitate the completion of various tasks, leading to maximize production. Furthermore, the number of companies can also influence palm oil production. Companies are where production activities take place and where all production factors converge. The more companies that produce palm oil, the higher the amount of palm oil products generated.

Table 3. Domain Value

Variable	Member Set	Domain
Demand	Low	[0 1601 3685]
	Medium	[1601 3685 6826]
	High	[3685 6826 7000]
Stock	Low	[0 368 972]
	Medium	[368 972 3127]
	High	[972 3127 3500]
Production	Low	[0 1817 3811]
	Medium	[1817 3811 6454]
	High	[3811 6454 6700]

Fuzzy logic starts with the concept of a fuzzy set. A *fuzzy set* is a set without a crisp, clearly defined boundary. This enables fuzzy logic to provide more accurate decisions according to uncertain conditions (Syarif et al. 2023). It can contain elements with only a partial degree of membership. To understand what a fuzzy set is, first consider the definition of a *classical set*. A classical set is a container that wholly includes or wholly excludes any given element.

a. Membership Function for the Demand Variable

The membership function for the fuzzy variable is developed based on the values present in the demand variable, as shown in Table 3.

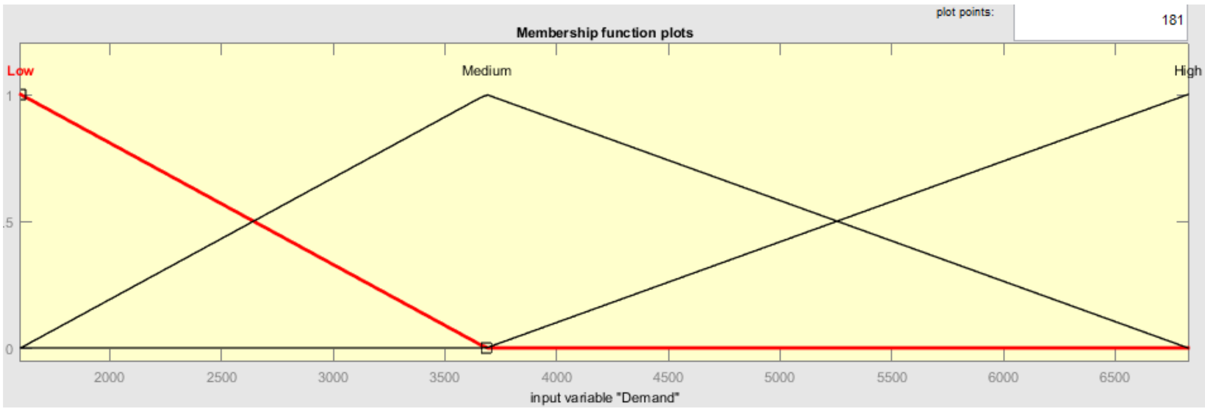

Figure 2. Membership function demand

The membership function for demand is as follows:

$$(Low)\begin{cases} x = 0 & ;0 \\ 0 < x < 1601 & ;\dfrac{x-a}{b-a} \\ x = 1601 & ;1 \\ 1601 < x \le 3685 & ;\dfrac{c-x}{c-b} \\ x > 3685 & ;0 \end{cases}$$

$$(Medium)\begin{cases} x < 1601 & ;0 \\ 1601 \le x < 3685 & ;\dfrac{x-a}{b-a} \\ x = 3685 & ;1 \\ 3685 < x \le 6826 & ;\dfrac{c-x}{c-b} \\ x > 6826 & ;0 \end{cases}$$

$$((High))\begin{cases} x < 3685 & ;0 \\ 3685 \le x < 6826 & ;\dfrac{x-a}{b-a} \\ x = 6826 & ;1 \\ 6826 < x \le 7000 & ;\dfrac{c-x}{c-b} \\ x > 7000 & ;0 \end{cases}$$

Example: If the demand values are 2.000; 4.500; and 8.500, then the fuzzy membership values for each set are as follows:

2.000 (Low) = $\frac{3685-2000}{3685-1601} = \frac{1685}{2084} = 0{,}8$

4.500 (Meidum) = $\frac{6826-4500}{6826-3685} = \frac{236}{3141} = 0{,}7$

8.500 (high) = 0

b. Membership Function for Stock Variable

The membership function for the fuzzy variable is constructed based on the values listed in the stock variable, as outlined in Table 3.

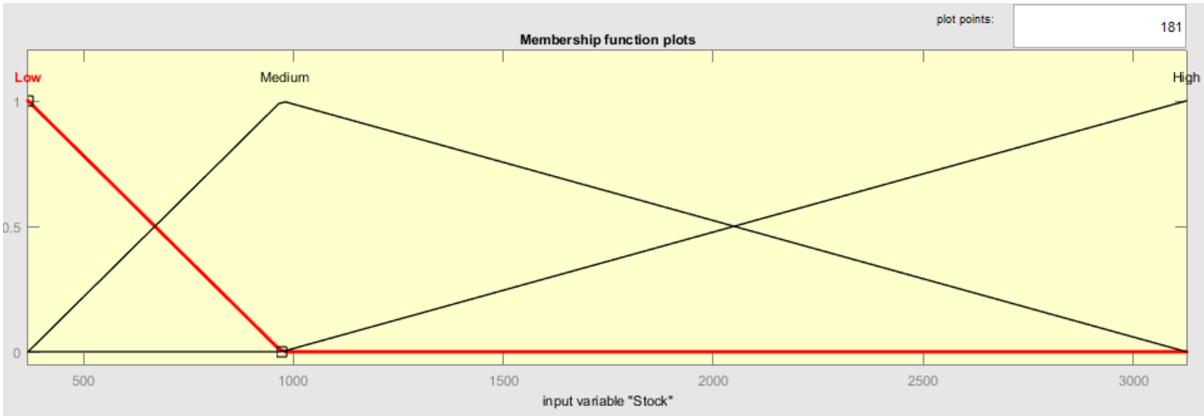

Figure 3. Membership function stock

The membership function for stock is as follows:

$$(Low)\begin{cases} x = 0 & ;0 \\ 0 < x < 368 & ;\dfrac{x-a}{b-a} \\ x = 368 & ;1 \\ 368 < x \leq 972 & ;\dfrac{c-x}{c-b} \\ x > 972 & ;\ 0 \end{cases}$$

$$(Medium)\begin{cases} x < 368 & ;0 \\ 368 \leq x < 972 & ;\dfrac{x-a}{b-a} \\ x = 972 & ;1 \\ 972 < x \leq 3127 & ;\dfrac{c-x}{c-b} \\ x > 3127 & ;\ 0 \end{cases}$$

$$(High)\begin{cases} x < 972 & ;0 \\ 972 \leq x < 3127 & ;\dfrac{x-a}{b-a} \\ x = 3127 & ;1 \\ 3127 < x \leq 3500 & ;\dfrac{c-x}{c-b} \\ x > 3500 & ;\ 0 \end{cases}$$

Example: If the stock values are 650.; 972; and 3.750, then the fuzzy membership values for each set are as follows:

650 (Low) = $\frac{972-650}{972-368} = \frac{322}{604} = 0{,}5$

972 (Medium) = 1

3750 (High) = 0

c. Membership Function for Production Variable

The membership function for the fuzzy variable is developed based on the values present in the production variable, as presented in Table 3.

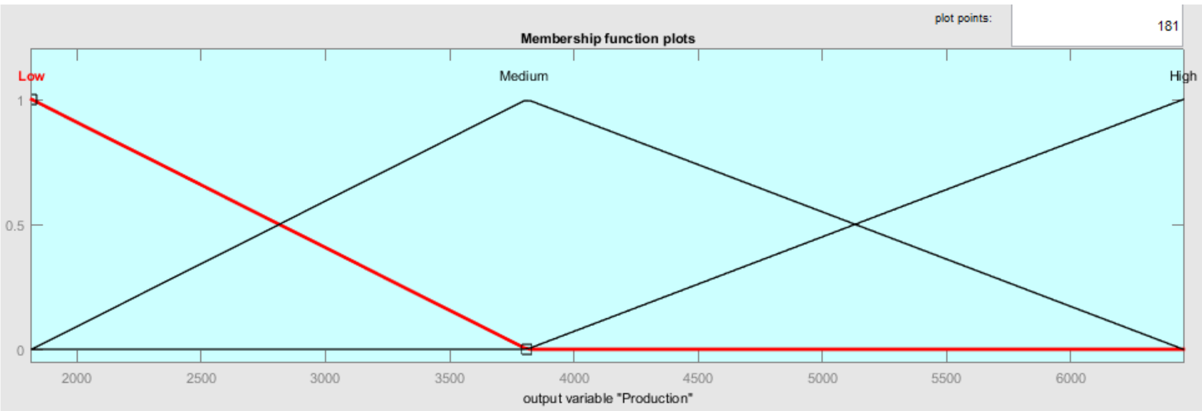

Figure 4. Membership function production

The membership function for production is as follows:

$$(Low)\begin{cases} x = 0 & ;0 \\ 0 < x < 1817 & ;\dfrac{x-a}{b-a} \\ x = 1817 & ;1 \\ 1817 < x \le 3811 & ;\dfrac{c-x}{c-b} \\ x > 3811 & ;0 \end{cases}$$

$$(Medium)\begin{cases} x < 1817 & ;0 \\ 1817 \le x < 3811 & ;\dfrac{x-a}{b-a} \\ x = 3811 & ;1 \\ 3811 < x \le 6454 & ;\dfrac{c-x}{c-b} \\ x > 6454 & ;0 \end{cases}$$

$$(High)\begin{cases} x < 3811 & ;0 \\ 3811 \le x < 6454 & ;\dfrac{x-a}{b-a} \\ x = 6454 & ;1 \\ 6454 < x \le 6700 & ;\dfrac{c-x}{c-b} \\ x > 6700 & ;0 \end{cases}$$

2. Definition of Fuzzy Rules and Variables.

Definition of Fuzzy Rules and Variables In this study, the fuzzy rule structure is determined by two input variables: Demand and Supply, and one output variable: Production. These rules are formulated in the form of "if-then" statements that describe the relationship between input conditions and output results. Below is a table that shows the fuzzy rules used:

Table 3. Fuzzy Rule Base

Rules	Demand	Stock	Production
1	Low	High	Low
2	Low	Medium	Low
3	Low	Low	Low
4	Medium	High	Low
5	Medium	Medium	Medium
6	Medium	Low	High
7	High	High	High
8	High	Medium	High
9	High	Low	High

Each of the above rules indicates how the combination of demand and supply affects the level of production. For example:

- Rule 1: If demand is low and supply is high, then production is low.
- Rule 5: If demand is medium and supply is medium, then production is high.
- Rule 9: If demand is high and supply is high, then production is high.

The fuzzy rule structure can be expressed as follows:
If Demand is (...) AND Supply is (...) Then Production is (...).

In this study, each combination of demand and supply values will produce a corresponding production value based on the previously established rules. Implementing Fuzzy Operators :

1. IF low demand (2000) and stock low (650) then low production = Min (0.8, 0.5) $\alpha1$ = 0,5
2. IF medium demand (4500) and stock medium (972) then medium production = Min (0.7, 1) $\alpha2$ = 0,7
3. IF high demand (3750) and stock medium (972) then high production = Min (0, 1) $\alpha3$ = 0

3. **Application of Implication Function**

α1 (Low) = 0,5
α2 (Medium) = 0,7
α3 (High) = 0

Calculation of functional implications
To get the value of X1 and X2 is using the same formula as the output data the membership function for production, using left side and right side rules.

- Low

  (X1) Left side equation :

$$\alpha 1 = \frac{x1 - a}{b - a}$$
$$0{,}5 = \frac{x1 - 0}{1817 - 0}$$
$$908{,}5 = X1 - 0$$
$$X1 = 909$$

  (X2) Right side equation :

$$\alpha 1 = \frac{c - x2}{c - b}$$
$$0{,}5 = \frac{3811 - x2}{3811 - 1817}$$
$$997 = 3811 - X2$$
$$X2 = 2814$$

- Medium

  (X1) Left side equation :

$$\alpha 2 = \frac{x1 - a}{b - a}$$
$$0{,}7 = \frac{x1 - 1817}{3811 - 1817}$$
$$1395{,}8 = X1 - 1817$$
$$X1 = 3213$$

  (X2) Right side equation :

$$\alpha 2 = \frac{c - x2}{c - b}$$
$$0{,}7 = \frac{6454 - x2}{6454 - 3811}$$
$$1850 = 6454 - X2$$
$$X2 = 4604$$

4. **Calculating Using MATLAB Software for Fuzzy Inference System with the Mamdani Method.**

MATLAB (Matrix Laboratory) is a program designed for numerical analysis and computation, and it serves as an advanced mathematical programming language based on the properties and structure of matrices. Developed by Mathworks, Inc., MATLAB is recognized as the most efficient software for matrix-based numerical calculations (Cahyono 2016). MATLAB is also accompanied by various built-in functions that are very helpful for working on tasks that are usually difficult to do in numerical processing, of course, with matrix-based numerical calculations (Rizki 2022). One of the fuzzy inference systems is the Mamdani method, which requires four steps to produce an output. One software that can be used to implement fuzzy logic systems is MATLAB (Matrix Laboratory). Within MATLAB, there are various tools that support the Mamdani method (Aenun 2014).

The first stage of the calculation using MATLAB software involves creating membership functions for each of the input and output variables. The inputs used in this study are two: demand input and inventory input, while the output is production. Next, we create a rule editor. The rule editor is used to create, edit, and display the rules in the fuzzy system.

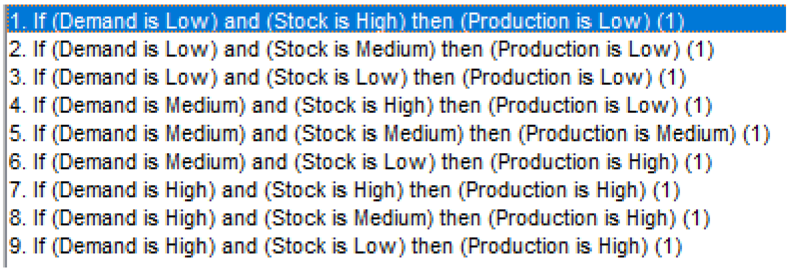

Figure 5. Rule editor

5. **Defuzzification**

Defuzzification is the final stage in a fuzzy logic system, aimed at converting each result from the inference engine, expressed in the form of fuzzy sets, into a real number. This process takes as input the fuzzy sets generated from the combination of various fuzzy rules. Meanwhile, the output produced is a value within the domain of those fuzzy sets. In other words, when provided with a fuzzy set within a certain range, a crisp value should be determinable as the outcome (Sutikno 2018). The defuzzification process is essential because fuzzy outputs or decisions are still represented as linguistic variables, which must be converted into crisp variables (Febriany 2019). The method of calculation employed is the centroid or center of gravity approach, which is the most frequently used technique. This method centers on determining the central point of the area created by the fuzzy sets derived from fuzzy rules. The first step is to calculate the area using the following calculations:

$$A1 = \frac{(909 - 0) \times 0{,}5}{2} = 227{,}25$$
$$A2 = (2814 - 909) \times 0{,}5 = 953$$
$$A3 = \frac{(3811 - 2814) \times 0{,}5}{2} = 249{,}25$$
$$A4 = \frac{(3213 - 1817) \times 0{,}5}{2} = 349$$
$$A5 = (4604 - 3213) \times 0{,}5 = 695{,}5$$
$$A6 = \frac{(6454 - 4604) \times 0{,}5}{2} = 462{,}5$$

Next step is to create the calculation of the composition function. This composition function is designed to calculate the moments.

$$f(x,a,b,c)\begin{cases} \frac{x-0}{1817-0} & ;0 \le x \le 909 \\ 0{,}5 & ;909 \le x \le 2814 \\ \frac{3811-x}{3811-1817} & ;2814 \le x \le 3811 \\ \frac{x-1817}{3811-1817} & ;1817 \le x \le 3213 \\ 0{,}7 & ;3213 \le x \le 4604 \\ \frac{6454-x}{6454-3811} & ;4604 \le x \le 6454 \\ x = 0 & ;x > 6454 \end{cases}$$

$$f(x,a,b,c)\begin{cases} 0{,}00055x & ;0 \le x \le 909 \\ 0{,}5 & ;909 \le x \le 2814 \\ 1{,}91 - 0{,}0005x & ;2814 \le x \le 3811 \\ 0{,}0005x - 0{,}91 & ;1817 \le x \le 3213 \\ 0{,}7 & ;3213 \le x \le 4604 \\ 2{,}44 - 0{,}00038x & ;4604 \le x \le 6454 \\ x = 0 & ;x > 6454 \end{cases}$$

The moment for each area is calculated using the integral formula of the membership function. Below are the results of the calculations:

$$M1 \int_{0}^{909} (0{,}00055z)\, z\, dz = \int_{0}^{909} (0{,}00055\, z^2)\, dz = 0{,}00018z^3 \,|_{0}^{909} = 135.196$$

$$M3 \int_{2814}^{3811} (1{,}91 - 0{,}0005z)\, z\, dz = \int_{2814}^{3811} (1{,}91z - 0{,}0005z^2)\, dz = 0{,}955z^2 - 0{,}00016z^3 \,|_{2814}^{3811}$$

$$= 1.017.178$$

$$M4 \int_{1817}^{3213} (0{,}0005z - 0{,}91)\, z\, dz = \int_{1817}^{3213} (0{,}0005z^2 - 0{,}91z)\, dz = 0{,}00016z^3 - 0{,}46z^2 \,|_{1817}^{3213}$$

$$= 1.117.163$$

$$M5 \int_{3213}^{4604} (0{,}7)z\, dz = \int_{3213}^{4604} (0{,}7z)\, dz = 0{,}35z^2 \,|_{3213}^{4604} = 3.805.706$$

$$M6 \int_{4604}^{6454} (2{,}44 - 0{,}00038z)\, z\, dz = \int_{4604}^{6454} (2{,}44z - 0{,}00038z^2)\, dz = 1{,}22z^2 - 0{,}00013z^3 \,|_{4604}^{6454}$$

$$= 2.695.988$$

The final step of defuzzification is to determine the value of z or the center point. The result of this calculation is the crisp value that will be used as the output of the fuzzy system. Below is the method for this calculation:

$$Z^* = \frac{\sum M}{\sum A} = \frac{135.196 + 1.773.079 + 1.017.178 + 1.117.163 + 3.805.706 + 2.695.988}{227{,}25 + 953 + 249{,}25 + 349 + 695{,}5 + 462{,}5}$$

$$= \frac{42177240}{11747} = \mathbf{3590}$$

The rule viewer is useful for understanding the fuzzy reasoning process within the system, including the mapping of inputs to each input variable, the application of operators and implication functions, as well as an emphasis on the defuzzification method (Dari 2018). The rules viewer represents the entire process that occurs in the Mamdani method.

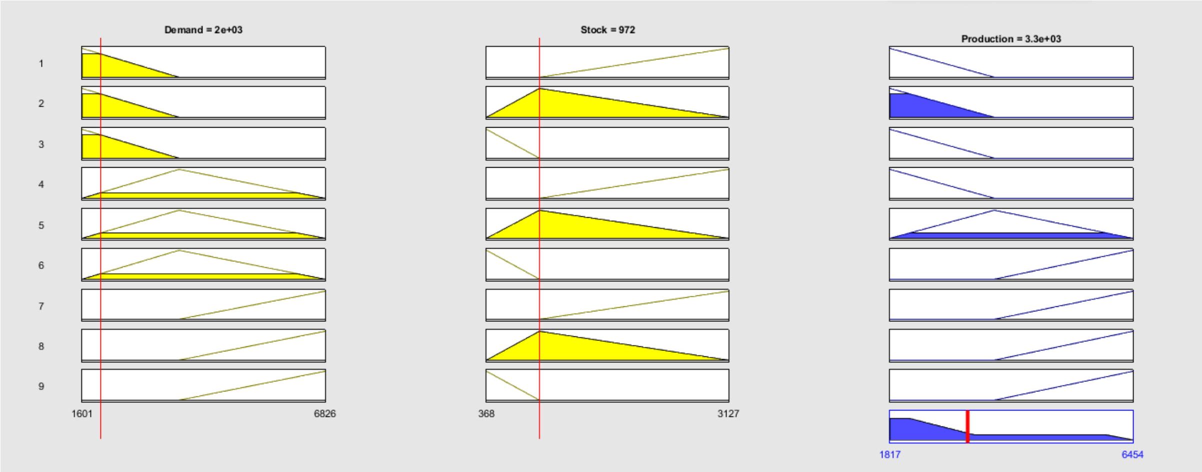

Figure 6. *Rules viewer*

The final stage involves creating a surface viewer. The surface viewer provides a visual representation of the overall plot from the Mamdani method. The Surface Viewer functions to display the relationship between input and output in the form of a three-dimensional graph (Dari 2018). By using the Surface Viewer, one can clearly see how various input parameters affect the output results.

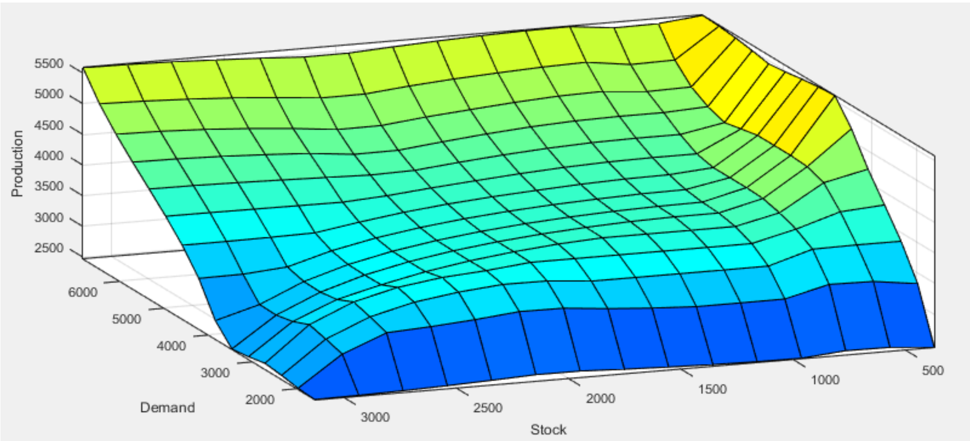

Figure 7. Surface viewer

CONCLUSION

The research investigates the application of the Mamdani fuzzy logic method to predict palm oil production based on consumer demand and supply data. The aim is to enhance the accuracy of production forecasts, which is critical for optimizing the palm oil industry in Indonesia. The methodology involves data collection on consumer demand and supply, formation of fuzzy sets, rule definition, and inference processing. The results indicate that the Mamdani method effectively correlates demand and supply levels with production outcomes, yielding consistent predictions compared to manual calculations. The findings conclude that implementing fuzzy logic can significantly improve decision-making in palm oil production, leading to more efficient and sustainable practices within the industry. This study highlights the potential of fuzzy logic applications in agricultural production systems for better resource management. It can be concluded that the results obtained from manual calculations are the same as those derived from calculations using fuzzy logic with the Mamdani method through the Mathlab application. This indicates that the Mathlab application has a high level of accuracy in presenting and analyzing data. Therefore, the presence of the Mathlab application can facilitate and support the effectiveness and efficiency of sustainable palm oil production.

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