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Implementation of Fuzzy Logic in Temperature Control Systems for Baking Ovens

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Abstract

To produce bread of the highest quality, it is essential to use the right type of bread oven, especially given the rapid growth of the bread industry. This study investigates the use of fuzzy logic as an automated method for controlling the baking oven temperature. By using fuzzy logic, it is expected that the oven can maintain an ideal temperature, resulting in consistent bread quality that meets expected standards. Fuzzy control systems differ from conventional control systems, which tend to be rigid.

The aim of this research is to develop a more efficient automated control system for regulating oven temperature to ensure consistent bread quality throughout the baking process. It is hoped that, with this automated control system, bread quality will not only improve but also enhance the production efficiency of the baking industry as a whole. Additionally, this study considers the type of bread being baked as a factor influencing the quality of the final product. Initial trials show that the fuzzy logic design produces satisfactory results, with the ability to adjust rules as needed.

Keywords:

Automation, Bread quality, Fuzzy logic, Oven temperature control

INTRODUCTION

The advancement of technology today can be utilized to optimize several tasks, one of which is the use of artificial intelligence, including fuzzy logic, to simplify work. Fuzzy logic is a data processing technique that handles uncertain information through approximate calculations (Cahyaningrum 2023). Fuzzy logic was first introduced by Jan Lukasiewicz in 1930, involving three main stages: fuzzification, inference, and defuzzification (Nisa et al. 2020). It operates on the concept of membership values between 0 and 1. The applications of fuzzy logic vary, such as determining safe limits for preservatives in canned foods (Mavani et al. 2024), assessing consumer acceptance of plant-based beverages (Kumar et al. 2021), and regulating temperature levels (Djara et.al 2019).

White bread is a type of bread made from wheat flour, fat, sugar, and water, fermented by yeast as a leavening agent, with or without additional food ingredients (Standar Nasional Indonesia 2018). White bread typically has a neutral taste, unlike whole wheat bread. Whole wheat bread is made from whole wheat, giving it a coarser texture, brown color, and high fiber content (Arwini 2021).

Bread must undergo a baking process to become a ready-to-eat product. Baking requires heat produced by equipment like an oven. The baking temperature significantly impacts the bread's final

quality. If the oven temperature is too high, the bread may burn, while if it's too low, the bread may be undercooked or fail to rise (Lestari et al. 2023). The modern era enables tasks like oven temperature control to be automated. Fuzzy logic can be used for this automation, as it can interpret vague or uncertain conditions and make decisions based on such inputs. Fuzzy logic is particularly effective for controlling oven temperature because it allows for adaptive adjustments in the baking process (Syarif et al. 2023).

METHODS

In line with previous research, Syarif et al. (2023) identified six main stages in the bread-making process: Formation and Expansion of Gas (Steps_1), Killing of yeast (Stepa_2), Gelatinization (Steps_3), Coagulation (Steps_4), Inactivation of enzymes (Steps_5), and Crust formation and browning (Steps_6).

Tabel 1. Detail *range* temperature in *Step of Baking*

NO	*Membership function*	White Bread	Wheat bread
1.	Steps 1	35°C – 70°C	
2.	Steps 2	60°C – 70°C	
3.	Steps 3	76°C	
4.	Steps 4	60°C – 70°C	
5.	Steps 5	80°C – 95°C	
6.	Steps 6	200°C – 210°C	195°C – 205°C

In this study, MATLAB was used as a platform to design a fuzzy control system. The available data is processed using the Mamdani-type fuzzy inference system method. Fuzzy Mamdani consists of 3 stages: fuzzification, rule evaluation, and defuzzification. The process begins with fuzzification, which involves converting crisp input into fuzzy input. Next, rules are applied to the fuzzy input, and each rule is evaluated based on the results from the fuzzification, producing a fuzzy output through the rule evaluation stage (Rule Evaluation).

The final stage is defuzzification, where the fuzzy output is converted back into a crisp output. In this study, there are three input variables: stage_of_baking, jenis_roti, and temperature, which are used to control the output in the form of Heater operation (on/off). The fuzzy logic framework developed in MATLAB can be seen in figure 1.

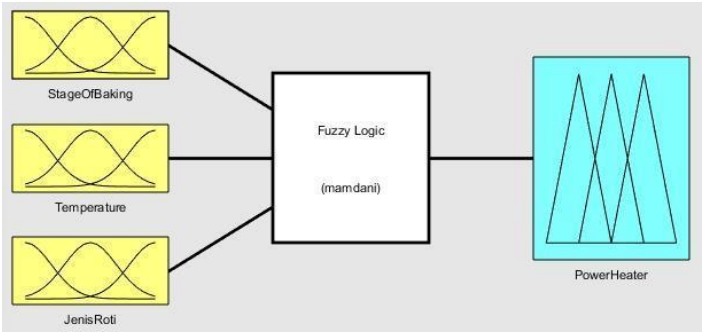

Figure 1. Framework of fuzzy logic for oven temperature control system

A. Fuzzification

In the fuzzification process, the step taken is to input fuzzy values. Fuzzification is the process of mapping crisp inputs into fuzzy sets in the form of membership functions (Winata et al. 2022). According to Subarja and Hendrik (2023), fuzzification is the process of converting input data into linguistic variables. According to Yunus (2015), fuzzification is the process of translating crisp inputs (definite numbers) into fuzzy sets. The input variables are divided into one or more fuzzy sets. In this study, there are three input data points: the variable stage of baking, the variable type

of bread, and the variable oven temperature. Meanwhile, the output to be controlled is the heating element (heater).

Tabel 2. *Input variables, membership function,* dan *range of membership*

Input variables	*Membership function*	*Range of membership*
Steps in baking	Steps 1	[0 0 1 1]
	Steps 2	[1 1.01 2 2]
	Steps 3	[1 2.01 3 3]
	Steps 4	[3 3.01 4 4]
	Steps 5	[4 4.01 5 5]
	Steps 6	[5 5.01 6 6]
Types of bread	White bread	[0 0 1 1]
	Wheat bread	[1 1.01 2 2]
Temperature	Low	[0 0 125]
	Medium	[125 150 275]
	High	[175 300 300]

B. Rule Evaluation

In the rule evaluation process, the step taken is to apply fuzzy input rules and evaluate each rule based on the input generated from the fuzzification process. According to Harahap (2019), rule evaluation is the process of taking fuzzified input values and applying them to the antecedents in the fuzzy rules, followed by application of these rules. These rules are designed to control the output variable. Fuzzy rules are generally structured in an IF-THEN format that includes conditions and conclusions. Table 3 presents the rules used in this evaluation stage.

Tabel 3. *Rules evaluation*

No	*Steps in baking*	*Types of bread*	*Temperatur*	*Power heater*
	Steps 1	Both	Low	On
	Steps 1	Both	Medium	Off
	Steps 1	Both	High	Off
	Steps 2	Both	Low	On
	Steps 2	Both	Medium	Off
	Steps 2	Both	High	Off
	Steps_3	Both	Low	On
	Steps_3	Both	Medium	Off
	Steps_3	Both	High	Off
	Steps_4	Both	Low	On
	Stage_4	Both	Medium	Off
	Steps_4	Both	High	Off
	Steps_5	Both	Low	On

	Steps_5	Both	Medium	On
	Steps_5	Both	High	Off
	Steps_6	White bread	Low	On
	Steps_6	White bread	Medium	On
	Steps_6	White bread	High	Off
	Steps_6	Wheat bread	Low	On
	Steps_6	Wheat bread	Medium	Off
	Steps_6	Wheat bread	High	Off

The baking temperature for both types of bread is the same from Stage_1 to Stage_5 of the Stage_of_Baking input variable. Therefore, the word "Both" found in Table 3 can indicate an input of White bread or Whole wheat bread. Since they have the same output, this method is used to create more effective rules.

C. Defuzzification

According to Furqon et al. (2019), defuzzification is the process of converting fuzzy outputs into crisp values according to the specified membership functions. In defuzzification, the input consists of fuzzy sets obtained from a combination of fuzzy rules. The resulting output is a value within the domain of these fuzzy sets. Thus, when provided with a fuzzy set within a certain range, a crisp value must be obtained as the output.

Table 4. Output variable, membership function, and membership range.

Input variables	Membership function	Membership Range
Heating Power	Off	[0 0 1 1]
	On	[1 1.01 2 2]

RESULTS AND DISCUSSION

Determination of Input and Output

A power heater is a part used in baking and culinary equipment that generates and regulates heat. Usually, it is in charge of supplying the temperature required to bake, cook, or heat goods to the appropriate level. Here, "power" means the intensity or strength of the heat output, which is frequently modifiable based on the type of food and the necessary baking or cooking procedure. A particular setting on the device, a number, or a percentage could be used to signify this modification. Operators must comprehend the "Power Heater" option in order to guarantee precise and reliable temperature regulation, which produces the best cooking outcomes.

The control of baking temperature is conducted using the Mamdani Fuzzy Logic method. The choice of the Mamdani method in this study is due to its suitability with fuzzy sets, data requirements, rules, and defuzzification, allowing for smooth value transitions, making fuzzy set changes gradual and

easy in calculations (Amni 2023). In the fuzzy logic calculations using the Mamdani method, several variables are required as inputs and outputs for the calculation method (Kartika et al. 2018). In this study, there are three input variables: Stage of baking, Type of bread, and Temperature. The output produced is Power Heater, indicating the appropriate baking temperature for the bread based on the combination of values from each input variable.

The term "stage of baking" describes the several stages of baking, such as preheating, initial rise, and final bake, each of which calls for a different temperature to guarantee the right development of texture and flavor. Because different breads (such as dense rye bread, soft rolls, or crispy baguettes) require varying baking temperatures and heating intensities to attain their ideal texture, moisture, and crust, the type of bread is also crucial. In order to ensure baking consistency, the temperature—which is the oven's current heat level—must be tracked and modified. The Mamdani Fuzzy Logic approach determines the ideal Power Heater setting by combining these variables, guaranteeing that every form of bread bakes in the most favorable conditions.

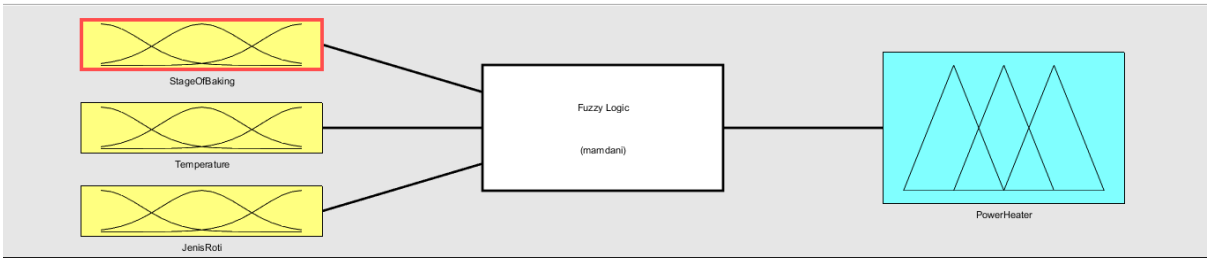

Figure 2. Fuzzy Logic Design using the Mamdani Method

Formation of fuzzy input and output sets

Triangular

Triangular distribution is a continuous distribution with three parameters: minimum value a, maximum value b, and the most likely value m, where a ≤ m ≤ b (Sugito 2017).

$$f(x;a,b,c) = \begin{cases} 0, & x \le a \\ \frac{x-a}{b-a}, & a \le x \le b \\ \frac{c-x}{c-b}, & b \le x \le c \\ 0, & c \le x \end{cases}$$

Trapezoidal

The trapezoidal method, or trapezoid method, is a numerical technique for solving integrals by dividing the interval into trapezoids of equal width. Then, the area of each trapezoid is calculated to obtain an approximation of the integral. This method can only be used for continuous functions (Meiliani et al 2024).

$$f(x;a,b,c,d) = \begin{cases} 0, & x \le a \\ \frac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \frac{d-x}{d-c}, & c \le x \le d \\ 0, & d \le x \end{cases}$$

Explanation:

a = the smallest domain value with a membership degree of zero

b = the smallest domain value with a membership degree of one
c = the largest domain value with a membership degree of one
d = the largest domain value with a membership degree of zero
x = the input value to be converted into a fuzzy number

A membership function is a curve that represents how input data points are mapped to their membership values (or degrees of membership), using an interval with a value range from 0 to 1 (Muhammad et al. 2019). According to Saputra 2019, the membership function is defined as a graphical representation of the degree of participation of each input. The membership function links weights with each processed input, indicates overlaps among inputs, and ultimately determines the output response. One way to obtain membership values is through function-based approaches. Several membership functions can be used, including the trapezoidal membership function (Wele et al. 2020).

1. Step of Baking
   - Member Function (Step 1)

$$f(x) \begin{cases} 0, x \leq 0 \\ \frac{x-0}{0-0}, 0 \leq x \leq 0 \\ 1, 0 \leq x \leq 1 \\ \frac{1-x}{1-1}, 1 \leq x \leq 1 \\ 0, 1 \leq x \end{cases}$$

   - Member Function (Step 2)

$$f(x) \begin{cases} 0, \ x \leq 0{,}9935 \\ \frac{x-0{,}9935}{1{,}003-0{,}9935}, 0{,}9935 \leq x \leq 1{,}003 \\ 1, \ 1{,}003 \leq x \leq 1{,}993 \\ \frac{1{,}993-x}{1{,}993-1{,}993}, 1{,}993 \leq x \leq 1{,}993 \\ 0, \ 1{,}993 \leq x \end{cases}$$

   - Member Function (Step 3)

$$f(x) \begin{cases} 0, x \leq 1 \\ \frac{x-1}{2,01-1}, 1 \leq x \leq 2,01 \\ 1, 2,01 \leq x \leq 3 \\ \frac{3-x}{3-3}, 3 \leq x \leq 3 \\ 0, 3 \leq x \end{cases}$$

- Member Function (Step 4)

$$f(x) \begin{cases} 0, x \leq 3 \\ \frac{x-3}{3,01-3}, 3 \leq x \leq 3,01 \\ 1, 3,01 \leq x \leq 4 \\ \frac{4-x}{4-4}, 4 \leq x \leq 4 \\ 0, 4 \leq x \end{cases}$$

- Member Function (Step 5)

$$f(x) \begin{cases} 0, x \leq 4 \\ \frac{x-4}{4,01-4}, 4 \leq x \leq 4,01 \\ 1, 4,01 \leq x \leq 5 \\ \frac{5-x}{5-5}, 5 \leq x \leq 5 \\ 0, 5 \leq x \end{cases}$$

- Member Function (Step 6)

$$f(x) \begin{cases} 0, x \leq 5 \\ \frac{x-5}{5,01-5}, 5 \leq x \leq 5,01 \\ 1, 5,01 \leq x \leq 6 \end{cases}$$

$$\begin{cases} \dfrac{6-x}{6-6}, 6 \le x \le 6 \\ 0, 6 \le x \end{cases}$$

Example: if the values of the stage of baking are 0.25; 0.9938; 2; 2.58; 4.05; 5.06. Then, the fuzzy membership values for each set are as follows:

0,25 (stage 1) = 1

0,9938 (stage 2) = $\frac{0,9938 - 0,9935}{1,003-0,9935} = \frac{0,0003}{0,0095} = 0,031$

2 (stage 3) = $\frac{2-1}{2,01-1} = \frac{1}{1,01} = 0,99$

2,58 (stage 4) = 0

4,05 (stage 5) = 1

5,06 (step 6) = 1

2. Types of Bread
   - Member Function (white bread)

$$f(x) \begin{cases} 0, 0 \\ \frac{x-0}{0-0}, 0 \le x \le 0 \\ 1, 0 \le x \le 1 \\ \dfrac{1-x}{1-1}, 1 \le x \le 1 \\ 0, 1 \le x \end{cases}$$

   - Member Function (wheat bread)

$$f(x) \begin{cases} 0, x \le 1 \\ \frac{x-1}{1,01-1}, 1 \le x \le 1,01 \\ 1, 1,01 \le x \le 2 \\ \dfrac{2-x}{2-2}, 2 \le x \le 2 \\ 0, 2 \le x \end{cases}$$

Example: If the bread type value is 0.25, 4. Then the fuzzy membership value for each set is as follows:
0.25 (white bread) = 1
4 (whole wheat bread) = 0

3. Temperature
    - Member Function (Low)

$$f(x) \begin{cases} 0, x \leq 0 \\ \frac{x-0}{0-0}, 0 \leq x \leq 0 \\ \frac{125-x}{125-0}, 0 \leq x \leq 125 \\ 0, 125 \leq x \end{cases}$$

    - Member Function (Medium)

$$f(x) \begin{cases} 0, x \leq 25 \\ \frac{x-25}{150-25}, 25 \leq x \leq 150 \\ \frac{275-x}{275-150}, 150 \leq x \leq 275 \\ 0, 275 \leq x \end{cases}$$

    - Member Function (High)

$$f(x) \begin{cases} 0, x \leq 175 \\ \frac{x-175}{300-175}, 175 \leq x \leq 300 \\ \frac{300-x}{300-300}, 175 \leq x \leq 300 \\ 0, 300 \leq x \end{cases}$$

Example: If the temperature values are 110, 175, and 250, the membership values for each fuzzy set are as follows:

110 (low) = $\frac{125-110}{125-0} = \frac{15}{125} = 0{,}12$

175 (medium) = $\frac{275-175}{275-150} = \frac{100}{125} = 0{,}8$

350 (high) = 0

4. Output Power of Heater
   - Member Function (off)

$$f(x) \begin{cases} 0, x \leq 0 \\ \frac{x-0}{0-0}, 0 \leq x \leq 0 \\ 1,\ 0 \leq x \leq 1 \\ \frac{1-x}{1-1}, 1 \leq x \leq 1 \\ 0,\ 1 \leq x \end{cases}$$

   - Member Function (on)

$$f(x) \begin{cases} 0, x \leq 1 \\ \frac{x-1}{1{,}01-1}, 1 \leq x \leq 1{,}01 \\ 1,\ 1{,}01 \leq x \leq 2 \\ \frac{2-x}{2-2}, 2 \leq x \leq 2 \\ 0,\ 2 \leq x \end{cases}$$

Definition of Fuzzy Rules and Variables

Fuzzy variables are the variables that will be discussed in the system (Rindengan and Langi 2019). Fuzzy rules and variables in this study, the fuzzy rule structure is determined by three input variables: baking stage, temperature, and type of bread, and one output variable: heating machine. The above rules show the combination of baking stage, temperature, and type of bread in relation to the heating machine, for example:

- Rule 16 : JIf the baking stage is CrustFormationAndBrowning and the temperature is low and the type of bread is white bread, then the heating machine is on.
- Rule 21 : JIf the baking stage is CrustFormationAndBrowning and the temperature is high and the type of bread is whole wheat bread, then the heating machine is off.

The fuzzy rule structure can be stated as follows: If the baking stage (...) and temperature (..) and type of bread (....), then the oven machine is (....).
In this study, each combination of baking stage, temperature, and type of bread will result in the corresponding oven machine value based on the rules set previously. The application of fuzzy operators:

1. If CrustFormationAndBrowning (5,06) and low temperature (110) and white bread (0,25), then the oven is on = min (1 : 0,12 ; 1) α1 = 0,12
2. If CrustFormationAndBrowning (5,06) and high temperature (250) and whole wheat bread (4), then the oven is off = min (1 ; 0 ; 0) α2 = 0

The application of the Implication Function
α1 (On) = 0,12
α2 (Off) = 0

The calculation in the implication to obtain X1 and X2 uses the same formula as the output data of the membership function, which is based on the left-hand and right-hand rules.

- On
  (X1) Left Side :
  $\alpha 1 = \frac{x-a}{b-a}$
  $0,12 = \frac{x-1}{1,01-1}$
  0,0012 = x-1
  X1 = 1,0012
  (X2) Right side :
  $\alpha 1 = \frac{d-x}{d-c}$
  $0,12 = \frac{2-x}{2-2}$
  0 = 2-x
  X2 = 2

Calculating using MATLAB for Fuzzy Inference System with the Mamdani method

Matrix Laboratory (MATLAB) is a software application based on matrices for its usage. The matrix in MATLAB is a simple matrix, making the application easy to use (Atina 2019). MATLAB is an application developed by Mathworks, Inc., and it is trusted by users as the most efficient application for matrix-based numerical calculations (Utami et al. 2023). MATLAB is equipped with built-in functions to assist users in solving problems that are difficult to handle in numerical processing (Fatwa et al 2022).

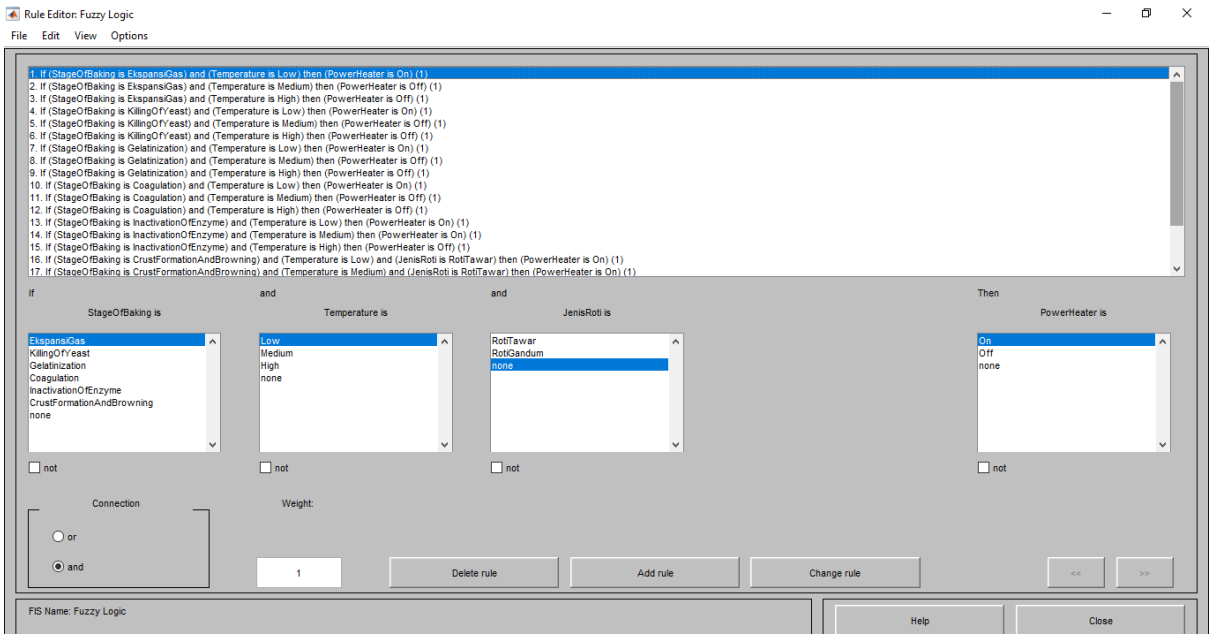

Figure 3. fuzzy logic rules

Based on the results of the fuzzy logic design for oven control that has been created, testing needs to be conducted. The testing in this study follows the research (Syarif et al. 2023), with a total of 20 trials, and the membership values for each input variable are randomly selected. The results of the trials are shown in Table 5.

Tabel 5. Test Results

No	*Stage of Baking*	*Jenis Roti*	*Temperatur*	*Predict*	*Output*	*Expected Output*
1	2.54	1.18	128	0.50	off	off
2	1.26	1.29	237	0.50	off	off
3	5.70	0.58	6	1.51	on	on
4	1.00	1.00	136	0.50	off	off
5	1.46	1.55	110	0.65	off	off
6	1.21	0.97	98	0.77	off	off
7	5.42	1.62	5	1.51	on	on
8	5.00	1.19	127	1.51	on	on
9	3.05	1.11	140	0.50	off	off
10	3.14	1.36	82	0.93	off	off
11	0.15	1.96	113	0.62	off	off
12	3.91	1.46	78	0.97	off	off
13	1.73	1.04	111	0.64	off	off
14	4.48	0.60	20	1.51	on	on
15	4.52	0.91	234	0.91	off	off
16	3.22	1.94	27	1.49	on	on
17	3.72	1.01	259	0.50	off	off
18	5.89	0.24	118	1.51	on	on
19	4.26	1.70	113	1.51	on	on
20	3.64	1.37	249	0.50	off	off

Based on the results obtained from 20 trials conducted using a random method, it was found that the use of fuzzy logic can produce an output that aligns with the research (Syarif et al. 2023). The predicted output is the result of the trial using MATLAB, while the expected output is the desired result based on the expected outcome from the given input.

The surface that represents the input values of each variable along with its output can be seen in Figure 4.

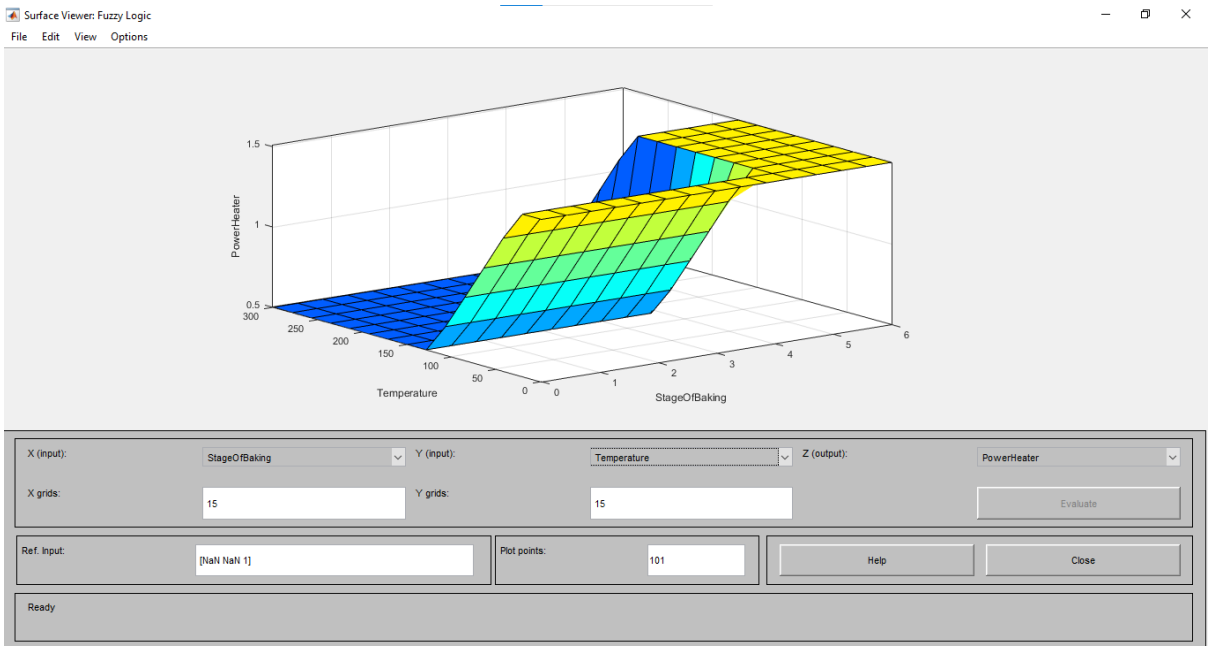

Figure 4. Surface result

Defuzzification

Defuzzification is the final calculation part in fuzzy logic by changing the results of the inference engine which are presented in the form of a fuzzy set into a real number (Sutikno 2018). The defuzzification stage is used to change fuzzy data into crisp data which refers to the previously created function (Neonbeni et al 2022). Defuzzification has five calculation methods in fuzzy mamdani including the centroid, Bisector, Mean of Maximum (MOM), Smallest of Maximum (SOM), and Largest of Maximum (LOM) methods (Gaddafi 2016). The defuzzification method most often used by researchers to solve fuzzy logic is the centroid method. The centroid method is often also called the COA (Center of Area) method. In this method, firm values are obtained based on the emphasis of the decision making results (Effendy et al 2018). This research uses centroids as a defuzzification solution.

Using the centroid formula to calculate the crisp value of PowerHeater:

$$\mathbf{P} = \int x \cdot \mu(x)\, dx \,/\, \int \mu(x)\, dx$$

Integral Calculation

1. Combined Membership Function:
   - On [0, 1] (Off): $\mu(x) = 0.2$
   - On [1, 2] (On): $\mu(x) = 0.5$

2. Numerator Integral
- On [0, 1]: $\int x \cdot 0.2\, dx = 0.1$
- On [1, 2]: $\int x \cdot 0.5\, dx = 0.75$
- Numerator total: 0.85

3.Denominator Integral:
- On [0, 1]: $\int 0.2\, dx = 0.2$
- On [1, 2]: $\int 0.5\, dx = 0.5$
- Denominator total: 0.7

4.Defuzzification Result:
$P = 0.85 / 0.7 \approx 1.214$

CONCLUSION

According to this study, the Mamdani approach of fuzzy logic has been successfully used to regulate the oven temperature during the bread-baking process. To ensure consistently high-quality bread, the fuzzy logic-based control system can automatically monitor and modify the oven temperature based on input data, including the type of bread being produced and the baking stages. In comparison to traditional control systems, experimental results demonstrate that the system can match expectations with smoother and more responsive temperature adjustments. On an industrial scale, it is anticipated that the use of fuzzy logic will increase manufacturing efficiency while preserving bread quality.

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