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Application of Fuzzy Logic to Determine the Condition of Candy Packaging Seals Based on Temperature, Pressure, and Heat-Sealing Duration

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Abstract

This study aims to optimize the heat-sealing process in candy packaging by applying the Mamdani Fuzzy Logic method to overcome variations in temperature, pressure, and sealing duration that often cause inconsistencies in seal quality. The fuzzy inference system was developed through the stages of fuzzification, rule evaluation, and defuzzification using the centroid method to model the nonlinear interaction between the three parameters. The model consists of 27 rules that produce the output variable Seal_Condition. The defuzzification results show a crisp value of 4.73, which indicates optimal seal conditions—tight enough without causing damage or melting of the packaging material. Test results prove that the fuzzy method provides more adaptive and stable control compared to conventional systems, thereby reducing seal defects and minimizing material waste. These findings confirm that the Mamdani Fuzzy Logic approach is effective and reliable as a decision support system for improving the efficiency and quality of the sealing process in the candy packaging industry.

Keywords: fuzzy logic, sealing process.

INTRODUCTION

The food packaging industry, particularly in confectionery products, requires precise processing to maintain product quality, texture, and shelf life. One critical stage is the heat-sealing process, where temperature, pressure, and heating duration must be optimally controlled to ensure the package is tightly sealed without damaging the material or the product inside. Inaccuracy in any of these parameters can reduce seal quality, increase defect rates, and cause excessive packaging material waste (Suwandi, 2025). However, the sealing system has nonlinear and time-varying characteristics, making conventional control methods such as Proportional-Integral-Derivative (PID) often unable to achieve stable and adaptive performance under dynamic production conditions (Zhang et al., 2023).

Addressing these limitations, the Mamdani fuzzy logic approach serves as an intelligent alternative capable of replicating human reasoning in managing system uncertainty and complexity (Tang & Ahmad, 2024). As a rule-based inference (RBI) system, fuzzy logic does not require a precise mathematical model and can adapt to variations in process parameters in real time. Several studies have demonstrated the effectiveness of fuzzy logic in industrial control systems, including gas distribution in modified atmosphere packaging (Zhang et al., 2023), temperature and humidity regulation in ambient conditioning systems (Tang & Ahmad, 2024), and control of automated manufacturing processes (Dinata, 2024). This technology has been shown to reduce oscillations, shorten stabilization time, and improve control accuracy compared with conventional PID systems.

Research on the specific application of Mamdani fuzzy logic in candy packaging sealing processes remains very limited. Most existing studies concentrate on fuzzy-based control systems for fresh food packaging or large-scale industrial settings, rather than on optimizing microparameters such as temperature, pressure, and sealing duration, which interact in complex ways. This research gap offers an important opportunity to explore the use of Mamdani fuzzy logic to enhance the consistency and efficiency of sealing processes in sugar confectionery or candy products (Suwandi, 2025).

METHODS

This study applies to the Mamdani fuzzy logic method to determine the optimal temperature, pressure, and sealing duration in the candy packaging process. This method was chosen because it can handle uncertainty in production parameters (Thalmeiner et al., 2025). Input data was obtained through a literature study used to identify relevant operational ranges and build the conceptual basis of the model (Snyder, 2019).

Table 1. Details on Temperature range, Pressure, and packaging sealing Duration

No.	Membership Function		Range	
			Min.	Max.
1	Temperature (°C)	Low	100	135
		Medium	130	155
		High	150	180
2	Pressure (bar)	Low	1	1.5
		Medium	1.25	3.5
		High	3.25	5
3	Duration (s)	Short	0	0.5
		Medium	0.35	0.85
		Long	0.7	1

Note. *Adapted from* "Observing the effect of pressure and temperature on the seal integrity of critical seal regions of various flexible bag designs," by I. Ilhan, R. ten Klooster, & I. Gibson, *Food Packaging and Shelf Life, 37*, 101088 (2023). https://doi.org/10.1016/j.fpsl.2023.101088

The Mamdani fuzzy controller was developed using MATLAB through three main stages: fuzzification, rule evaluation, and defuzzification. Fuzzy input values (Temperature, Pressure, Duration) are converted to membership degrees, processed through linguistic rules, and then converted back into fuzzy outputs that represent the Seal Condition. The fuzzy logic framework implemented in MATLAB is shown in Figure 1.

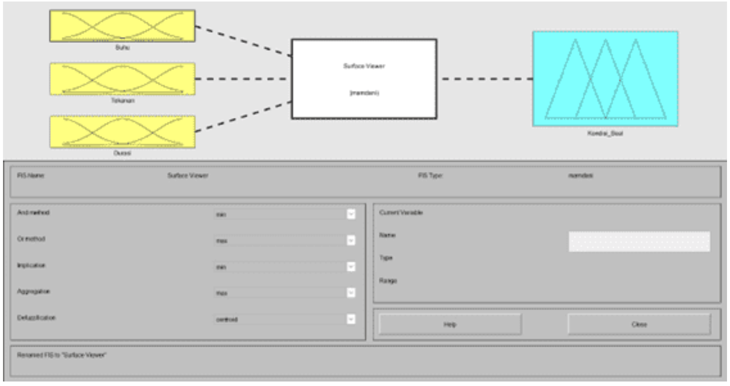

Figure 1. Framework of fuzzy logic for heat sealing control system

2.1 Fuzzification

Fuzzification is the initial stage in the Mamdani fuzzy system, where definite input values are converted into membership degrees through a predetermined membership function (Winata et al., 2018). This stage allows numerical data to be processed in linguistic form for further rule evaluation (Tang & Ahmad, 2024). In this study, fuzzification was applied to three input variables: temperature, pressure, and duration.

Table 2. Input variables, membership function, and range of membership

No.	Input Variables	Membership Function	Range of Membership
1	Temperature (°C)	Low	[100 100 135]
		Medium	[130 145 155]
		High	[150 180 180]
2	Pressure (bar)	Low	[1 1 1.5]
		Medium	[1.25 2.25 3.5]
		High	[3.25 5 5]
3	Duration (s)	Short	[0 0 0.5]
		Medium	[0.35 0.6 0.85]
		Long	[0.7 1 1]

2.2 Fuzzy Rules

Fuzzy rules in the rule base are applied to fuzzified inputs to determine system outputs through IF–THEN statements. These rules describe the relationship between input conditions and expected outputs, enabling the Mamdani inference process to run efficiently (Suwandi et al., 2025).

Figure 2. Fuzzy Rules

The Fuzzy Rules process in Figure 2 has 27 rules and 3 output results, namely Less Tight, Optimal, and Melt.

2.3 Defuzzification

Defuzzification is the final stage in the Mamdani system, where aggregated fuzzy outputs are converted into crisp values (Suwandi et al., 2025). This study uses the centroid (center of gravity) method as a defuzzification technique to produce stable and representative outputs. Model validation is carried out by examining the consistency of membership functions, evaluating rule behavior, and checking the suitability of defuzzification results with the expected sealing performance.

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

Input Variables	Membership Function	Range of Membership
	Less Tight	[0 0 4]
Seal_Condition	Optimal	[3 5 7]
	Melt	[6 10 10]

RESULTS AND DISCUSSION

Determination of Input and Output

In the food industry, packaging quality control is a crucial aspect that determines the safety and shelf life of products. The quality of the "Seal_Condition," which is directly influenced by process variables such as Temperature, Pressure, and Duration, must be established and strictly controlled (Kusnandar et al., 2021). Accurate and consistent determination of the output for this "Seal_Condition" is vital to prevent contamination, maintain freshness, and ensure product compliance with food safety standards and applicable industry regulations (Badan Pengawas Obat dan Makanan Republik Indonesia, 2019).

The Mamdani Fuzzy Logic method was chosen to implement control or condition assessment in the observed process. The selection of Mamdani for this study is based on its advantages in managing fuzzy sets, rules, and the defuzzification process, which facilitates a smooth transition of values, allowing the calculation and adjustment of fuzzy sets to be carried out gradually and efficiently (Amni, 2023). Input and output variables are important elements in Mamdani fuzzy logic calculations (Kartika et al., 2018). In this study, three variables serve as inputs: Temperature, Pressure, and Duration. The combination of values from each of these input variables will produce an output in the form of “Seal_Condition” which indicates the status or quality of the seal based on the combination of operational parameters applied.

Formation of Fuzzy Input and Output Sets

The Triangular Distribution is defined as a type of continuous probability distribution characterized by three specific parameters: the minimum value (a), the maximum value (b), and the most frequently occurring value (m), with the condition a ≤ m ≤ b (Sugito, 2017). This distribution is generally represented using the notation Triangular (a, m, b). The model is then mathematically described through its probability density function, which is formulated as follows:

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

Explanation:
a = The lowest domain value where the degree of membership is zero (non-member).
b = The smallest domain value that reaches a membership degree of one (full member).
c = The largest domain value that still has a membership degree of one (full member).
x = The numerical input value (crisp) that will be converted into a fuzzy number (fuzzified).

1. Temperature
   - Member Function (Low)

$$f(x)\begin{cases} 0, x \le 100 \\ \dfrac{x-100}{135\ -100}, 100 \le x \le 135 \\ 0, 135\ \le x \end{cases}$$

   - Member Function (Medium)

$$f(x)\begin{cases} 0, x \le 130 \\ \dfrac{x-130}{155\ -130}, 130 \le x \le 155 \\ 0, 155\ \le x \end{cases}$$

   - Member Function (High)

$$f(x)\begin{cases} 0, x \le 150 \\ \dfrac{x-150}{180\ -150}, 150 \le x \le 180 \\ 0, 180\ \le x \end{cases}$$

Example = If the temperature values are 110, 145, and 170, the membership value for each fuzzy logic set are as follows:

110 (low) = $\frac{110-100}{135-100} = \frac{10}{35} = 0{,}29$

145 (medium) = $\frac{145-130}{155-130} = \frac{15}{25} = 0{,}60$

170 (high) = $\frac{170-150}{180-150} = \frac{20}{30} = 0{,}67$

2. Pressure

- Member Function (Low)

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

- Member Function (Medium)

$$f(x)\begin{cases} 0, x \leq 1{,}25 \\ \dfrac{x-1{,}25}{3{,}5-1{,}25}, 1{,}25 \leq x \leq 3{,}5 \\ 0, 3{,}5 \leq x \end{cases}$$

- Member Function (High)

$$f(x)\begin{cases} 0, x \leq 3{,}25 \\ \dfrac{x-3{,}25}{5-3{,}25}, 3{,}25 \leq x \leq 5 \\ 0, 5 \leq x \end{cases}$$

Example = If the pressure values are 2, 4, and 5.5, the membership values for each fuzzy set are as follows:

2 (low) = $\frac{2-1}{1{,}5-1} = \frac{1}{0{,}5} = 2$

4 (medium) = $\frac{4-1{,}25}{3{,}25-1{,}25} = \frac{2{,}75}{2} = 1{,}38$

5,5 (high) = $\frac{5{,}5-3{,}25}{5-3{,}25} = \frac{2{,}25}{1{,}75} = 1{,}29$

3. Duration

- Member Function (Short)

$$f(x)\begin{cases} 0, x \leq 0 \\ \dfrac{x-0}{0{,}5-0}, 0 \leq x \leq 0{,}5 \\ 0, 0{,}5 \leq x \end{cases}$$

- Member Function (Medium)

$$f(x)\begin{cases} 0, x \leq 0{,}35 \\ \dfrac{x-0{,}35}{0{,}85-0{,}35}, 0{,}35 \leq x \leq 0{,}85 \\ 0, 0{,}85 \leq x \end{cases}$$

- Member Function (Long)

$$f(x)\begin{cases} 0, x \leq 0{,}7 \\ \dfrac{x-0{,}7}{1-0{,}7}, 0{,}7 \leq x \leq 1 \\ 0, 1 \leq x \end{cases}$$

Example = If the duration values are 0.25, 0.6, and 0.9, the membership values for each fuzzy set are as follows:

0,25 (low) = $\frac{0{,}25-0}{0{,}5-0} = \frac{0{,}25}{0{,}5} = 0{,}5$

0,6 (medium) = $\frac{0{,}6-0{,}35}{0{,}85-0{,}35} = \frac{0{,}25}{0{,}5} = 0{,}5$

0,9 (high) = $\frac{0{,}9-0{,}7}{1-0{,}7} = \frac{0{,}2}{0{,}3} = 0{,}67$

4. Output Seal_Condition
    - Member Function (Less tight)

$$f(x)\begin{cases} 0, x \leq 0 \\ \dfrac{x-0}{4-0}, 0 \leq x \leq 4 \\ 0, 4 \leq x \end{cases}$$

    - Member Function (Optimal)

$$f(x)\begin{cases} 0, x \leq 3 \\ \dfrac{x-3}{7-3}, 3 \leq x \leq 7 \\ 0, 7 \leq x \end{cases}$$

    - Member Function (Melt)

$$f(x)\begin{cases} 0, x \leq 6 \\ \dfrac{x-6}{10-6}, 6 \leq x \leq 10 \\ 0, 10 \leq x \end{cases}$$

Definition of Fuzzy Rules and Variable

The variables that are the focus of analysis or main discussion in this system are called Fuzzy Variables (Rindengan & Langi, 2019). In this study, the fuzzy rule structure is determined by three input variables: Temperature, Pressure, and Duration will result in the corresponding Seal_Condition based on the established rules.

Example Rules:

- Rule 3: If the Temperature is Medium, the Pressure is Medium, and the Duration is Medium, then the Seal_Condition is Optimal.
- Rule 4: If the Temperature is Medium, the Pressure is High, and the Duration is Medium, then the Seal_Condition is Melt.

The fuzzy rule structure can be expressed as follows:
If Temperature is (...) and Pressure is (...) and Duration is (...), then Seal_Condition is (...).

The application of fuzzy operators:

1. If medium temperature (145°C) and medium pressure (2,25 bar) and medium duration (0.6 s), then seal condition = optimal = min (1.0; 1.0; 1.0) → $\alpha_1 = 1.0$
2. If medium temperature (140°C) and high pressure (5 bar) and medium duration (0.6 s), then seal condition = melt = min (0.67; 1.0; 1.0) → $\alpha_2 = 0.67$

Calculating using MATLAB for Fuzzy Inference System with the Mamdani method

Matrix Laboratory (MATLAB) is a software environment designed based on matrices for all its operations (Cahyono, 2013). The simplified matrix structure in MATLAB makes this application easy to use, even for novice users. Developed by MathWorks, Inc., MATLAB is recognized as one of the most efficient and reliable applications for matrix-based numerical processing (Kinanti et al., 2025). This application also comes with a variety of built-in functions that play an important role in helping users solve complex numerical computation problems (Muthoharoh et al., 2021).

After the fuzzy logic design for heat sealing control was completed, the testing phase became the next important step. This testing was conducted following the procedures established in the study (Maulana et al., 2025). But it differed in the total number of trials, which involved only 27 experiments. In each experiment, the membership values for each input variable were selected randomly. The results obtained from the entire series of experiments are then presented in Table 5.

Table 5. Trial Results

No	Temperature (°C)	Pressure (bar)	Duration (s)	Output
1	121.86	1.32	0.38	2.47
2	112.48	1.09	0.2	1.46
3	128.27	1.07	0.25	1.79
4	105.32	1.44	0.14	1.79
5	110.17	1.07	0.4	1.78
6	123.21	1.39	0.2	1.66
7	108.17	1.26	0.11	1.54
8	134.03	1.05	0.42	3.8
9	103.94	1.5	0.19	1.74
10	134.63	2.24	0.62	5
11	131.35	2.41	0.64	5

12	133.3	2.65	0.55	5
13	136.02	2.45	0.47	5
14	151.39	2.48	0.36	5.4
15	145.12	3.42	0.59	6.91
16	150.41	2.81	0.36	5.15
17	153.92	2.63	0.51	6.92
18	151.16	3.39	0.36	5.94
19	158.75	4.06	0.8	8.3
20	166.02	3.8	0.84	8.32
21	156.73	4.99	0.92	8.24
22	161.28	4.5	0.89	8.37
23	158.12	3.87	0.93	8.28
24	156.34	4.9	0.96	8.23
25	157.53	3.6	0.97	8.22
26	174.11	4.99	0.77	8.33
27	169.65	4.03	0.74	8.42

Three-dimensional visualization on surface graphs showing the relationship between input values of each variable and the system output can be seen in Figures 3 and 4.

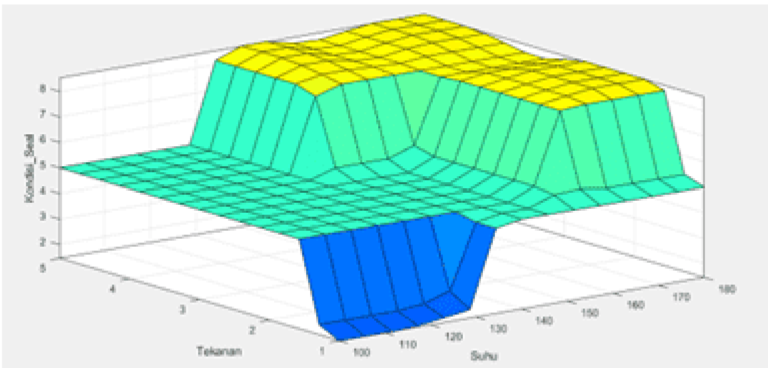

Figure 3. Surface result of input variables Temperature and Pressure

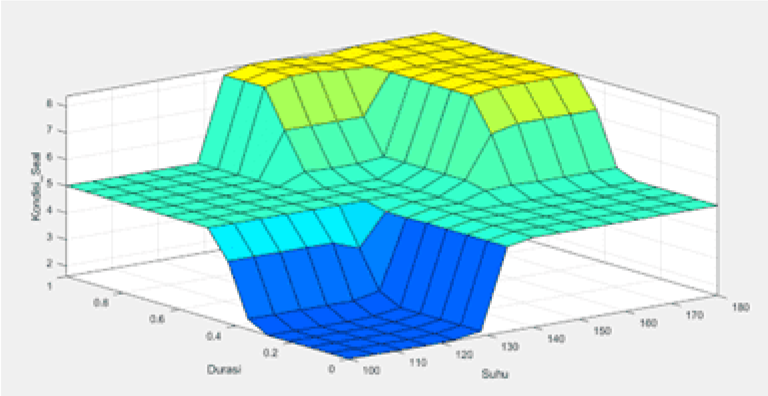

Figure 4. Surface result of input variables Temperature and Duration

Deffuzification

Defuzzification is the last step in a fuzzy logic system that converts the inference results, which are still represented as fuzzy sets, into crisp numerical values that can be quantitatively interpreted. This stage is essential because the fuzzy system output is linguistic in nature and must be transformed into a numeric value representing the final decision (Khairo & Sitepu, 2020). The process is conducted based on previously defined membership functions to ensure consistency between the fuzzy logic reasoning and the resulting decisions. Various methods can be applied in the defuzzification process, including the centroid, bisector, mean of maximum (MOM), smallest of maximum (SOM), and largest of maximum (LOM) techniques. Among these, the centroid or center of area (COA) method is the most used, as it produces more representative and stable results when data variability occurs (Al-Nahhas et al., 2024). Therefore, this study employs the centroid method as the defuzzification approach to obtain an optimal and reliable crisp output.

Using the centroid formula to calculate the crisp value of seal condition:

$$Z = \frac{\int x \,.\mu(x)dx}{\int \mu(x)dx}$$

Explanation:
Z = crisp output value (defuzzification result),
x = output variable, and
μ(x) = membership degree at each value of x.

1. Combined Membership Function

Based on the fuzzy inference results from the combination of temperature, pressure, and duration, three active membership sets were obtained as follows:

- [0, 4] ⟶ μ(x) = 0,3 (less tight)
- [3, 7] ⟶ μ(x) = 0,6 (optimum)
- [6, 10] ⟶ μ(x) = 0,2 (melt)

2. Numerator Integral

- [0, 4] = ∫x. 0,3 dx = 2,4
- [3, 7] = ∫x. 0,6 dx = 12
- [6, 10] = ∫x. 0,2 dx = 6,4

Total Numerator = 20,8

3. Denominator Integral

- [0, 4] = ∫0,3 dx = 1,2
- [3, 7] = ∫0,6 dx = 2,4
- [6, 10] = ∫0,2 dx = 0,8

Total Denominator = 4,4

4. Defuzzification Result

$$Z = \frac{\int x \cdot \mu(x)dx}{\int \mu(x)dx}$$

$$Z = \frac{20,8}{4,4} = 4,73$$

The defuzzification result of 4.73 indicates that the combination of temperature, pressure, and sealing duration produces a seal condition that is closest to the ideal state, neither too loose (less tight) nor reaching the melting stage. Thus, the fuzzy system provides a recommendation for a stable and efficient sealing condition at this point of equilibrium.

CONCLUSION

The heat-sealing process in candy packaging can be optimized using the Mamdani Fuzzy Logic method, which can handle the uncertainty and nonlinear nature of the parameters of temperature, pressure, and sealing duration. Through the stages of fuzzification, rule evaluation, and defuzzification using the centroid method, the system successfully modeled the relationship between these three variables and produced a crisp value of 4.73, which indicates optimal sealing conditions—tight enough without causing the packaging to melt. Test results show that fuzzy logic provides more adaptive, stable, and consistent control compared to conventional methods, thereby reducing sealing defects, maintaining product quality, and minimizing material waste. Overall, this study proves that fuzzy logic is an effective and reliable approach to improving the efficiency and quality of the sealing process in the candy packaging industry.

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