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FUZZY LOGIC APPROACH TO FOREST FIRE RISK ASSESSMENT IN TANJUNG PUTTING NATIONAL PARK

Rani Natalia Purba [1], **Esther Sorta Mauli Nababan** [2*], **Prana Ugiana Gio** [3], **Zahedi** [4], **Muhammad Romi Syahputra** [5]

[1,2,3,4,5]*Mathematics Study Program, Faculty of Mathematics and Natural Sciences, Universitas Sumatera Utara*
Jln. Dr. T. Mansur No. 9, Padang Bulan, Medan, 20222, Indonesia

Corresponding author's e-mail: * **esther@usu.ac.id**

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ABSTRACT

In implementing fuzzy logic, the Sugeno fuzzy method faces several challenges, such as issues in determining the fuzzy rule base and the occurrence of undefined outputs (defuzzification) with values of 0/0. This study examines the application of the Sugeno fuzzy method in identifying the level of forest fire risk by considering various variables. The variables are temperature, humidity, and wind speed. The model is developed using fuzzy rules constructed based on the relationships among the variables. The test results show that after modifying the membership function boundaries to decimal values approaching the original lower bounds, the Zero-Order Sugeno fuzzy method can produce an average forest fire risk level of 68.83 (high category) in Tanjung Puting National Park. In addition, applying the First-Order Sugeno fuzzy method produces a multiple linear regression model that can be applied within the rule base, resulting in an average forest fire risk level of 68.89 (high category) at the same location. During the evaluation phase, the First-Order Sugeno model achieved a lower RMSE value (15.47) than the Zero-Order model (16.03), indicating that it is more suitable for handling extreme conditions such as dangerous spikes in risk. Therefore, this approach has the potential to serve as an effective early warning system for forest fire mitigation, supporting decision-making processes.

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1. INTRODUCTION

Fuzzy logic can be defined as a mathematical approach that helps humans deal with uncertainty and ambiguity in the decision-making process. It means that not all concepts can be stated in terms of true or false in the real world [1]. Fuzzy logic was first introduced by Professor Lotfi Zadeh, Head of the Department of Electrical Engineering at Berkeley, in 1965 [2]. Fuzzy logic can be utilized in decision-making systems or for predicting events in various fields, including economics, geophysics, medicine, and others. This is because fuzzy logic is used in measuring various events or phenomena that are vague or unclear and uncertain [3]. In the context of data uncertainty, fuzzy logic provides an efficient approach to handling ambiguity, as it is capable of interpreting data to yield information with relative or subjective definitions [4].

One of the calculation methods in fuzzy logic is the Fuzzy Sugeno method [5]. The Fuzzy Sugeno method was first introduced by Takagi Sugeno Kang in 1985. This method is similar to the Fuzzy Mamdani method, but it produces outputs in the form of constants or linear equations, unlike the Fuzzy Mamdani method, which yields outputs in the form of fuzzy sets. The Fuzzy Sugeno method has consequences that are not in the form of fuzzy sets, but are linear equations with variables corresponding to the input variables [6]. This method is known for its efficiency in modeling systems that require rule-based decisions with numerically calculable results. The Fuzzy Sugeno method also typically provides more accurate results and requires only a few rules to describe complex and highly nonlinear systems, generally needing fewer rules than models based on Fuzzy Mamdani [7].

In a study conducted by Yasin et al. (2024), the Fuzzy Sugeno method was applied to the operation of landslide disaster control systems, utilizing two sensors to detect movement and humidity in the soil, yielding results as expected [8]. This is also relevant to the research by Alves et al. (2024), which states that the Fuzzy Sugeno method has advantages, namely its simplicity in defining the rule base structure and a low number of hyperparameters [7]. Then, in a study conducted by Muhtadi et al. (2024), it was demonstrated that fuzzy inference systems can be utilized to assess the risk levels of forest fires [9]. This is supported by research by Budiyanto et al. (2020), which states that fuzzy inference systems, such as Fuzzy Sugeno, can be applied to fire detection systems using wireless sensor networks [10]. This is relevant to the fact that forest fires are among the disasters that have received significant attention in many countries, including Indonesia. Between 2015 and 2020, the total area of forest and land burned in Indonesia reached 5,641,337 hectares. However, from 2020 to July 31, 2021, this figure declined significantly, with the burned area amounting to only 160,104 hectares. Despite this decrease, continuous efforts are being made to prevent forest and land fires in Indonesia [11].

The ability of Sugeno Fuzzy to make predictions is also expected to enable accurate identification of the level of forest fire risk, as precise risk identification can serve as a foundation for making informed decisions. Unlike previous research that focused solely on the application of Fuzzy Sugeno, this study specifically examines the use of the Fuzzy Sugeno method in risk level assessment, including challenges in determining fuzzy rules (rule base) and handling output values of $\frac{0}{0}$. As such, this study contributes to the literature by offering insights into overcoming challenges in Fuzzy Sugeno implementations, thereby enhancing its applicability in risk identification using a mathematical approach.

2. RESEARCH METHODS

2.1 Research Methods

This research is a quantitative study based on literature, conducting a literature review to examine several reference sources, including books, journals, and previous research on the Fuzzy Sugeno method. The calculation process in this study utilizes the Anaconda3 software due to its superior compatibility with various data sources (CSV, JSON, SQL, API) and the availability of thousands of Python libraries for data processing, visualization, and model evaluation. This makes it well-suited for real-time assessment of forest fire risk levels [12].

2.2 Research Stages

The steps of this research are as follows.

2.2.1 Conducting a Review of the Fuzzy Sugeno Method in Identifying Risk Levels

The fire risk forecast of this study is based on a Forest Fire Weather Index (FWI), which predicts the level of forest fire risk using simple meteorological data (temperature, humidity, and wind speed) [13]. In the assessment process, risk level measurements are made, including Fuzzy Sugeno Order Zero and Fuzzy Sugeno Order One. In the output generation process, there are four stages performed using the Fuzzy Sugeno method, as follows.

1. Fuzzification

   Fuzzification is the process of transforming input that initially has a definite value into linguistic variables using membership functions stored in the fuzzy knowledge base [7]. At this stage, the membership function is defined, which is a curve that maps input points to their membership values within the interval of 0 to 1 [14]. In addition, at this stage, the universe of discourse for each variable is also determined in order to form the appropriate fuzzy sets [15]. In this study, increasing linear, decreasing linear, and triangular membership functions are used.

   a. Increasing Linear

   Let μ(x) represent the membership value of a fuzzy set at input point *x*, where *x* is the input value, *a* is the lower bound, and *b* is the upper bound. Accordingly, the increasing linear membership function can be expressed as shown in Eq. (1) [16].

$$\mu|x| = \begin{cases} 0, x \leq a, \\ \dfrac{x-a}{b-a}; a \leq x \leq b, \\ 1; x \geq b. \end{cases} \tag{1}$$

   b. Decreasing Linear

   Let μ(x) represent the membership value of a fuzzy set at input point *x*, where *x* is the input value, *a* is the lower bound, and *b* is the upper bound. Accordingly, the decreasing linear membership function can be expressed as shown in Eq. (2) [16].

$$\mu|x| = \begin{cases} 0, x \geq b, \\ \dfrac{b-x}{b-a}; a \leq x \leq b, \\ 1; x \leq a. \end{cases} \tag{2}$$

   c. Triangle

   Let μ(x) be the membership value of a fuzzy set at the input point *x*, where *x* is the input value, *a* is the lower bound, *b* is the midpoint, and *c* is the upper bound. Accordingly, the triangle membership function can be expressed as shown in Eq. (3) [17].

$$\mu|x| = \begin{cases} 0, x \leq a \text{ } or \text{ } x \geq c \\ \dfrac{x-a}{b-a}; a \leq x \leq b \\ \dfrac{c-x}{c-b}; b \leq x \leq c \end{cases} \tag{3}$$

2. Determining Fuzzy Rules

   In this process, rules are formulated in the form of fuzzy implications, which are used to illustrate the relationship between input variables and output variables [18]. The Fuzzy Sugeno model consists of a set of fuzzy functional rules used to describe a nonlinear system through linear subsystems [6]. The *i*-th fuzzy rule of the Fuzzy Sugeno model is represented as shown in Eq. (4).

$$IF \ x \ is \ A \ and \ y \ is \ B, THEN \ z \ = \ f(x,y). \tag{4}$$

3. Rules Composition

   At this stage, inference is obtained from the $\sum_{r=1}^{R} \alpha_r z_r$ along with the correlation between rules, which is the calculation of the results from R rules, where α_r is the *fire strength* for rule-r, and z_r is the output of the antecedent of rule-r.

4. Defuzzification

   If the fuzzy set is given within a certain range, it must be able to produce a specific crisp value as output [19]. Its form is as Eq. (5).

$$Z = \frac{\sum_{r=1}^{R} \alpha_r z_r}{\sum_{r=1}^{R} \alpha_r}, \tag{5}$$

where:

Z: risk level variable,

α_r: α –predicate (fire strength) dari of rule–r,

z_r: output in the antecedent of rule–r.

In the calculation of First Order Sugeno Fuzzy, fuzzy rules are first sought using Multiple Linear Regression to determine the regression coefficients and their significance, which can be used to answer the existing hypotheses. The general model of multiple linear regression can be written as (6) [20].

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon, \tag{6}$$

where:

Y: dependent variable;

$X_1, X_2, \ldots, X_n$: variable;

β_0: intercept (constant);

$\beta_1, \beta_2, \ldots, \beta_n$: regression coefficients;

ε: error of the model.

the process of calculating forest fire risk levels using the Zero-Order Sugeno fuzzy method is illustrated in Fig. 1.

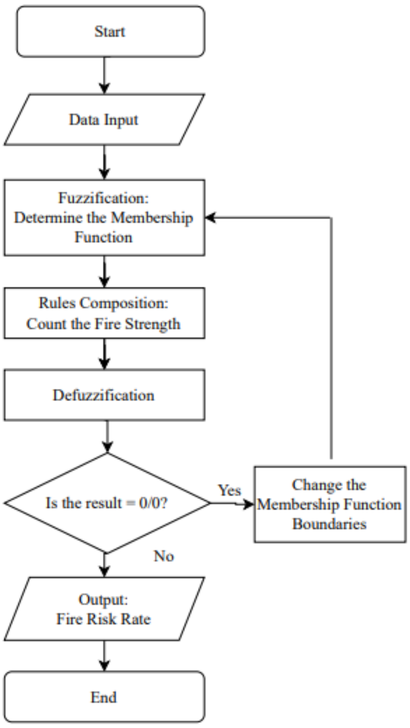

Figure 1. Flowchart of Forest Fire Risk Level Calculation Using Zero-Order Sugeno Fuzzy Method

Then, the process of First-Order Sugeno Fuzzy model development using multiple linear regression is shown in Fig. 2.

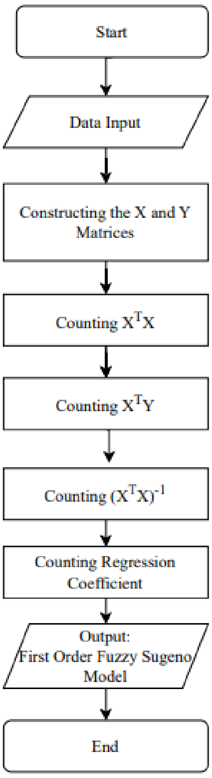

Figure 2. Flowchart of First-Order Sugeno Fuzzy Model Development Using Multiple Linear Regression

2.2.2 Model Evaluation

The Root Mean Squared Error (RMSE) is a commonly used metric for evaluating the performance of a predictive model. Given a dataset consisting of n actual observations $y(y_i, i = 1,2, \dots, n)$ and n corresponding predicted values $\hat{y}$. The RMSE is calculated to assess the accuracy of the model's predictions [21]. The formula can be written as Eq. (7).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}, \tag{7}$$

where:

y_i: the i-th actual value;

$\hat{y}_i$: the i-th prediction value;

n: total number of data.

3. RESULTS AND DISCUSSION

3.1 Data Descriptions

The data in this research are from the journal by Muhtadi et al. (2024) [9], which includes 3 variables: temperature, humidity, and wind speed in Tanjung Puting National Park from June 4, 2023, to June 18, 2023, as the Table 1.

Table 1. Weather Data at Tanjung Puting National Park (June 4-June 18, 2023)

No	Temperature (℃)	Humidity (%)	Wind Speed (Km/h)
1	30	82	13
2	30	81	12
3	31	79	13
4	30	80	14
5	32	75	16
6	32	71	17
7	32	72	17
8	32	75	16
9	31	78	15
10	32	76	15
11	32	76	14
12	32	76	14
13	31	77	14
14	31	77	13
15	32	75	14

Data source: *Muhtadi et al., 2024* [9]

3.2 Measuring the Level of Forest Fire Risk Using Zero-order Fuzzy Sugeno

3.2.1 Fuzzification

Table 2. Range of Linguistic Values of Temperature

Linguistic Values	Range (℃)
Low	0- 25
Medium	25- 30
High	30- 40

Data Source*: Muhtadi et al., 2024* [9]

The decreasing linear membership function is used for low temperatures, the triangular function for medium temperatures, and the increasing linear function for high temperatures. Here are the membership functions for the temperature variable, as shown in Table 2, using Equations Table 2 by using Eqs. (1), (2), and (3).

$$\mu_{low} = \begin{cases} 1, x \leq 0 \\ \dfrac{25 - x}{25 - 0}; 0 \leq x \leq 25 \\ 0; x \geq 25 \end{cases}$$

$$\mu_{high} = \begin{cases} 0, x \leq 25 \ or\ x \geq 30 \\ \dfrac{x - 25}{27 - 25}; 25 \leq x \leq 27 \\ \dfrac{30 - x}{30 - 27}; 27 \leq x \leq 30 \end{cases}$$

$$\mu_{medium} = \begin{cases} 0, x \leq 30 \\ \dfrac{x - 30}{40 - 30}; 30 \leq x \leq 40 \\ 1; x \geq 40 \end{cases}$$

Table 3. Range of Linguistic Values of Humidity

Linguistic Values	Range (%)
Low	0- 75
Medium	75- 80
High	80- 100

Data source: *Muhtadi et al., 2024* **[9]**

The downward linear membership function is used for low humidity, the triangular function for medium humidity, and the upward linear function for high humidity. Here are the membership functions for the humidity variable based on Table 3 using Eqs. (1), (2), and (3).

$$\mu_{low} = \begin{cases} 0, x \leq 0 \\ \dfrac{80 - x}{80 - 75}; 0 \leq x \leq 75 \\ 1; x \geq 75 \end{cases}$$

$$\mu_{high} = \begin{cases} 0, x \leq 80 \\ \dfrac{x - 80}{100 - 80}; 80 \leq x \leq 100 \\ 1; x \geq 100 \end{cases}$$

$$\mu_{medium} = \begin{cases} 0, x \leq 75 \text{ or } x \geq 80 \\ \frac{x - 75}{78 - 75}, 75 \leq x \leq 78 \\ \frac{80 - x}{80 - 78}, 78 \leq x \leq 80 \end{cases}$$

The downward linear membership function is used for calm wind speeds, the triangular function for moderate and high wind speeds, and the upward linear function for storm wind speeds.

Table 4. Range of Linguistic Values of Wind Speed

Linguistic Values	Range (Km/h)
Calm	0-7
Medium	7-13
High	13-20
Storm	20-42

Data source: *Muhtadi et al., 2024* [9]

Here are the membership functions of the wind speed variable based on Table 4 by using Eqs. (1), (2), and (3).

$$\mu_{calm} = \begin{cases} 0, x \geq 7 \\ \frac{7 - x}{7 - 0}; 0 \leq x \leq 7 \\ 1; x \leq 0 \end{cases}$$

$$\mu_{medium} = \begin{cases} 0, x \leq 7 \text{ or } x \geq 13 \\ \frac{x - 7}{10 - 7}, 7 \leq x \leq 10 \\ \frac{13 - x}{13 - 10}, 10 \leq x \leq 13 \end{cases}$$

$$\mu_{high} = \begin{cases} 0, x \leq 7 \text{ or } x \geq 20 \\ \frac{x - 13}{16 - 13}, 13 \leq x \leq 16 \\ \frac{20 - x}{20 - 16}, 16 \leq x \leq 20 \end{cases}$$

$$\mu_{storm} = \begin{cases} 0, x \leq 20 \\ \frac{x - 20}{42 - 20}; 20 \leq x \leq 42 \\ 1; x \geq 42 \end{cases}$$

In the case of forest fires, the Fire Weather Index (FWI) output ranges from 0 to 100. The range for each linguistic value is shown in Table 5.

Table 5. Range of Variable Levels of Forest Fire Risk

Linguistic Values	*Range*
Low	0-25
Medium	25-50
High	50-100

Data source: *Muhtadi et al., 2024* [9]

In the First Order Sugeno Fuzzy method, the output is constant. Therefore, the constant values are taken as the midpoints of the fuzzy membership on the wildfire risk level variable, serving as a numerical representation of the linguistic categories: the low category, valued at 15; the medium category, valued at 35; and the high category, valued at 70.

3.2.2 Determining Fuzzy Rules

There are 36 Fuzzy rules used as follows as Table 6.

Table 6. Fuzzy Rules in Determining Forest Fire Risk

No	Temperature	Humidity	Wind Speed	*Output*
1	Low	Low	Calm	Low
2	Low	Low	Medium	Low
3	Low	Low	High	Low
4	Low	Medium	Storm	Medium
5	Low	Medium	Calm	Low
6	Low	Medium	Medium	Low
7	Low	High	High	Low
8	Low	High	Storm	Low
9	Low	High	Calm	Low

No	Temperature	Humidity	Wind Speed	*Output*
10	Low	Low	Medium	Low
11	Low	Low	High	Low
12	Low	Low	Storm	Low
13	Medium	Medium	Calm	Low
14	Medium	Medium	Medium	Low
15	Medium	Medium	High	Medium
16	Medium	High	Storm	High
17	Medium	High	Calm	Low
18	Medium	High	Medium	Low
19	Medium	Low	High	Medium
20	Medium	Low	Storm	High
21	Medium	Low	Calm	Low
22	Medium	Medium	Medium	Low
23	Medium	Medium	High	Medium
24	Medium	Medium	Storm	Medium
25	High	High	Calm	Medium
26	High	High	Medium	High
27	High	High	High	High
28	High	Low	Storm	High
29	High	Low	Calm	Medium
30	High	Low	Medium	Medium
31	High	Medium	High	High
32	High	Medium	Storm	High
33	High	Medium	Calm	Medium
34	High	High	Medium	Medium
35	High	High	High	High
36	High	High	Storm	High

Data source: *Muhtadi et al., 2024* [9]

In the First Order Sugeno Fuzzy method, the output is constant. Therefore, the constant values are taken as the midpoints of the fuzzy membership on the wildfire risk level variable, serving as a numerical representation of the linguistic categories: the low category, valued at 15; the medium category, valued at 35; and the high category, valued at 70.

3.2.3 Rules Composition

For example, using the first test data with temperature $= 30°C$, humidity $= 82\%$, and wind speed $= 13\ km/h$ will produce the *fire strength* (α) calculation for each rule as follows.

R1: *IF* temperature is low, humidity is low, *AND* wind speed is high, *THEN* the risk = 15.

Low Temperature (Linear Decrease)

$$\mu_{low} = 0$$

Low Humidity (Linear Decrease)

$$\mu_{low} = 1$$

High Wind Speed (Linear Increase)

$$\mu_{high} = \frac{13 - 13}{16 - 13} = \frac{0}{3} = 0$$

Obtained the value of α = 0 (obtained from the minimum membership degree of rule 1, which is 0). The calculation results of the membership degree using the first data set are fully shown in Fig. 3.

```
Rule: If temperature is Low, humidity is Low, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Low, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Low, wind speed is High, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Low, wind speed is Storm, then the risk = 35, with α = 0.00
Rule: If temperature is Low, humidity is Medium, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Medium, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Medium, wind speed is High, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Medium, wind speed is Storm, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is High, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is High, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is High, wind speed is High, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is High, wind speed is Storm, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is Low, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is Low, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is Low, wind speed is High, then the risk = 35, with α = 0.00
Rule: If temperature is Medium, humidity is Low, wind speed is Storm, then the risk = 70, with α = 0.00
Rule: If temperature is Medium, humidity is Medium, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is Medium, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is Medium, wind speed is High, then the risk = 35, with α = 0.00
Rule: If temperature is Medium, humidity is Medium, wind speed is Storm, then the risk = 70, with α = 0.00
Rule: If temperature is Medium, humidity is High, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is High, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is High, wind speed is High, then the risk = 35, with α = 0.00
Rule: If temperature is Medium, humidity is High, wind speed is Storm, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is Low, wind speed is Calm, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is Low, wind speed is Medium, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is Low, wind speed is High, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is Low, wind speed is Storm, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is Medium, wind speed is Calm, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is Medium, wind speed is Medium, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is Medium, wind speed is High, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is Medium, wind speed is Storm, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is High, wind speed is Calm, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is High, wind speed is Medium, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is High, wind speed is High, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is High, wind speed is Storm, then the risk = 70, with α = 0.00
```

Figure 3. Fire Strength of the First Test Data using Python

3.2.4 Defuzzification

In the defuzzification stage, the product of each α value is summed with the z value from the fuzzy rules, then divided by the total of all α value. It can be seen that all alpha values in each rule are zero; therefore, when multiplied by their respective z values, they also result in zero.

$$\sum(\alpha \times z) = 0,$$

and

$$\sum \alpha = 0.$$

Thus, the defuzzification value Z^* is:

$$Z^* = \frac{(\alpha \times z)}{\alpha} = \frac{0}{0}.$$

Therefore, the risk level of forest fire for a temperature of 30°C, humidity of 82%, and wind speed of 13 km/h is $\frac{0}{0}$. In other words, the level of risk cannot be determined. This occurs because the test data has one of its variable values at the boundary of the defined membership function.

Table 7. Table of Forest Fire Risk Level Calculation Results Using Python Program

No	Temperature $(°C)$	Humidity (%)	Wind Speed (Km/h)	Forest Fire Risk Level
1	30	82	13	$\frac{0}{0}$
2	30	81	12	$\frac{0}{0}$
3	31	79	13	$\frac{0}{0}$
4	30	80	14	$\frac{0}{0}$
5	32	75	16	70 (High)
6	32	71	17	70 (High)
7	32	72	17	70 (High)
8	32	75	16	70 (High)
9	31	78	15	70 (High)
10	32	76	15	70 (High)
11	32	76	14	70 (High)
12	32	76	14	70 (High)
13	31	77	14	70 (High)
14	31	77	13	$\frac{0}{0}$
15	32	75	14	70 (High)

Based on Table 7, it can be seen that Fuzzy Sugeno has a weakness when the test data used is at the limits of the defined membership function. To address this issue, the boundaries of its membership function can be adjusted to values that are closer to the previously used limits.

First, the membership function limits of the temperature variable can be changed as follows.

$$\mu_{low} = \begin{cases} 1;\ x \leq 0 \\ \dfrac{24.99 - x}{24.99 - 0};0 \leq x \leq 24.99 \\ 0; x \geq 24.99 \end{cases} \qquad \mu_{medium} = \begin{cases} 0;\ x \leq 24.99\ or\ x \geq 29.99 \\ \dfrac{x - 24.99}{26.99 - 24.99}; 24.99 \leq x \leq 26.99 \\ \dfrac{29.99 - x}{29.99 - 26.99}; 26.99 \leq x \leq 29.99 \end{cases}$$

$$\mu_{high} = \begin{cases} 0; x \leq 29.99 \\ \dfrac{x - 29.99}{39.99 - 29.99}; 29.99 \leq x \leq 39.99 \\ 1; x \geq 39.99 \end{cases}$$

Then, the membership function of the air humidity variable can also be adjusted to the following limits.

$$\mu_{low} = \begin{cases} 0;\ x \leq 0 \\ \dfrac{79.99 - x}{79.99 - 74.99};0 \leq x \leq 74.99 \\ 1; x \geq 74.99 \end{cases} \qquad \mu_{medium} = \begin{cases} 0;\ x \leq 74.99\ or\ x \geq 79.99 \\ \dfrac{x - 74.99}{79.99 - 74.99}; 74.99 \leq x \leq 79.99 \\ \dfrac{79.99 - x}{79.99 - 77.99}; 77.99 \leq x \leq 79.99 \end{cases}$$

$$\mu_{high} = \begin{cases} 0; x \leq 79.99 \\ \dfrac{x - 79.99}{99.99 - 79.99}; 79.99 \leq x \leq 99.99 \\ 1; x \geq 99.99 \end{cases}$$

Lastly, the membership function of the wind speed variable can be changed as follows.

$$\mu_{low} = \begin{cases} 0;\ x \geq 6.99 \\ \dfrac{6.99 - x}{6.99 - 0};0 \leq x \leq 6.99 \\ 1; x \leq 0 \end{cases} \qquad \mu_{medium} = \begin{cases} 0;\ x \leq 6.99\ or\ x \geq 12.99 \\ \dfrac{x - 6.99}{9.99 - 6.99}; 6.99 \leq x \leq 9.99 \\ \dfrac{12.99 - x}{12.99 - 9.99}; 9.99 \leq x \leq 12.99 \end{cases}$$

$$\mu_{high} = \begin{cases} 0; x \leq 6.99\ or\ x \geq 19.99 \\ \dfrac{x - 12.99}{15.99 - 12.99}; 12.99 \leq x \leq 15.99 \\ \dfrac{29.99 - x}{19.99 - 15.99}; 15.99 \leq x \leq 19.99 \end{cases} \qquad \mu_{storm} = \begin{cases} 0; x \leq 19.99 \\ \dfrac{x - 19.99}{41{,}99 - 19.99}; 19.99 \leq x \leq 41.99 \\ 1; x \geq 41.99 \end{cases}$$

After the membership function limits are changed, the value (α) for all rules can be calculated. For example, taking the first test data that previously resulted in an uncertain value, namely temperature = 30°C, humidity = 82%, and wind speed = 13 km/h, the following is the calculation of fire strength (α) for each rule.

R1: IF low temperature, low humidity, AND high wind speed, THEN risk = 15. Low Temperature (Linear Decrease)

$$\mu_{low} = 0.$$

Low Humidity (Linear Decrease)

$$\mu_{low} = 0.$$

High Wind Speed (Linear Increase)

$$\mu_{high} = \frac{14 - 13}{16 - 14} = \frac{1}{2} = 0.5.$$

Obtained the value of $\alpha = 0$ (obtained from the minimum degree of membership of rule 1, which is 0). The calculation results of the membership degree (fire strength) using the first data set are fully shown in Fig. 4.

```
Rule: If temperature is Low, humidity is Low, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Low, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Low, wind speed is High, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Low, wind speed is Storm, then the risk = 35, with α = 0.00
Rule: If temperature is Low, humidity is Medium, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Medium, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Medium, wind speed is High, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is Medium, wind speed is Storm, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is High, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is High, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is High, wind speed is High, then the risk = 15, with α = 0.00
Rule: If temperature is Low, humidity is High, wind speed is Storm, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is Low, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is Low, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is Low, wind speed is High, then the risk = 35, with α = 0.00
Rule: If temperature is Medium, humidity is Low, wind speed is Storm, then the risk = 70, with α = 0.00
Rule: If temperature is Medium, humidity is Medium, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is Medium, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is Medium, wind speed is High, then the risk = 35, with α = 0.00
Rule: If temperature is Medium, humidity is Medium, wind speed is Storm, then the risk = 70, with α = 0.00
Rule: If temperature is Medium, humidity is High, wind speed is Calm, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is High, wind speed is Medium, then the risk = 15, with α = 0.00
Rule: If temperature is Medium, humidity is High, wind speed is High, then the risk = 35, with α = 0.00
Rule: If temperature is Medium, humidity is High, wind speed is Storm, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is Low, wind speed is Calm, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is Low, wind speed is Medium, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is Low, wind speed is High, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is Low, wind speed is Storm, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is Medium, wind speed is Calm, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is Medium, wind speed is Medium, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is Medium, wind speed is High, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is Medium, wind speed is Storm, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is High, wind speed is Calm, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is High, wind speed is Medium, then the risk = 35, with α = 0.00
Rule: If temperature is High, humidity is High, wind speed is High, then the risk = 70, with α = 0.00
Rule: If temperature is High, humidity is High, wind speed is Storm, then the risk = 70, with α = 0.00
```

Figure 4. Fire Strength of the First Test Data using Python after Membership Functions Updated

After calculating the membership degree values of each rule (α), the next step is to calculate its defuzzification value.

$$\alpha \times z = 0.101 \times 70 = 0.07.$$

The results of the calculations are as follows.

$$\sum \alpha \times z = 0.07,$$

while the total α:

$$\sum \alpha = 0.001.$$

Thus, the defuzzification value Z^* is:

$$Z^* = \frac{\sum(\alpha \times z)}{\sum \alpha} = \frac{0.07}{0.001} = 70.$$

Table 8. Table of Forest Fire Risk Level After Membership Functions Updated

No	Temperature (℃)	Humidity (%)	Wind Speed (Km/h)	Forest Fire Risk Level
1	30	82	13	70 (High)
2	30	81	12	52.5 (Medium)
3	31	79	13	70 (High)
4	30	80	14	70 (High)
5	32	75	16	70 (High)
6	32	71	17	70 (High)
7	32	72	17	70 (High)
8	32	75	16	70 (High)
9	31	78	15	70 (High)
10	32	76	15	70 (High)
11	32	76	14	70 (High)
12	32	76	14	70 (High)
13	31	77	14	70 (High)
14	31	77	13	70 (High)
15	32	75	14	70 (High)

From Table 8, it can be seen that all test data produce defuzzification values (level of forest fire risk) that are defined and fall into the high category. In other words, changing the limits of the membership function can affect the results of the defuzzification calculation. Additionally, the average value of the forest fire risk level can be calculated as follows.

$$\bar{Z}^* = \frac{1}{15}\sum_{i=1}^{15} Z_i^* = \frac{1{,}032.5}{15} = 66.83.$$

Therefore, the average forest fire risk level in Tanjung Puting National Park from June 4, 2023, to June 18, 2023, as determined by the Zero-Order Fuzzy Sugeno method is $\bar{Z}^* = 66.83$ (high category).

3.3 Measuring the Level of Forest Fire Risk Using First-Order Fuzzy Sugeno

In this case, global regression that encompasses all data can be used since there is only one dataset as the Table 9.

Table 9. Forest Fire Risk Level Data in Tanjung Puting National Park (June 4 - June 18, 2023)

No	Temperature (℃)	Humidity (%)	Wind Speed (Km/h)	Forest Fire Risk Level
1	30	82	13	35
2	30	81	12	15
3	31	79	13	70
4	30	80	14	35
5	32	75	16	70
6	32	71	17	70
7	32	72	17	70
8	32	75	16	70
9	31	78	15	70
10	32	76	15	70
11	32	76	14	70
12	32	76	14	70
13	31	77	14	70
14	31	77	13	70
15	32	75	14	70

Data source: *Muhtadi et al., 2024* [9]

First, the formation of matrices X and Y is carried out.

$$X = \begin{bmatrix} 1 & 30 & 82 & 13 \\ 1 & 30 & 81 & 12 \\ 1 & 31 & 79 & 13 \\ 1 & 30 & 80 & 14 \\ 1 & 32 & 75 & 16 \\ 1 & 32 & 71 & 17 \\ 1 & 32 & 72 & 17 \\ 1 & 32 & 75 & 16 \\ 1 & 31 & 78 & 15 \\ 1 & 32 & 76 & 15 \\ 1 & 32 & 76 & 14 \\ 1 & 32 & 76 & 14 \\ 1 & 31 & 77 & 14 \\ 1 & 31 & 77 & 13 \\ 1 & 32 & 75 & 14 \end{bmatrix}.$$

Second, counted $X^T X$.

$$X^T X = \begin{bmatrix} 15 & 470 & 1150 & 217 \\ 470 & 14736 & 36003 & 6811 \\ 1150 & 36003 & 88296 & 16583 \\ 217 & 6811 & 16583 & 3171 \end{bmatrix}.$$

Third, counted $X^T Y$.

$$X^T Y = \begin{bmatrix} 1032.5 \\ 32375 \\ 72082.5 \\ 19.480 \end{bmatrix}.$$

Fourth, the inverse is calculated $(X^T X)^{-1}$.

$$(X^T X)^{-1} = \begin{bmatrix} 1631.63 & -25.27 & -9.57 & -7.35 \\ -25.27 & 0.47 & 0.13 & 0.05 \\ -9.57 & 0.13 & 0.061 & 0.056 \\ -7.35 & 0.046 & 0.056 & 0.11 \end{bmatrix}.$$

Finally, the regression coefficient β is calculated.

$$\beta = (X^T X)^{-1} X^T Y$$

$$\beta = \begin{bmatrix} -112.35 \\ 3.14 \\ 0.79 \\ 1.54 \end{bmatrix}.$$

Therefore, the regression model obtained is:

$$\hat{Y} = -112.35 + 3.14 \times Temperature + 0.79 \times Humidity + 1.54 \times Wind\ Speed. \quad (8)$$

3.4 Case Example

In this case, test data (Muhtadi et al., 2024) was used employing the Fuzzy Sugeno Global Regression Model with the aid of Anaconda3 software, specifically Jupyter Notebook. For a temperature of 30°C, humidity of 82%, and wind speed of 13 km/h, the wildfire risk level obtained using Eq. (8) is:

$$\hat{Y} = -16.6407 + 0.5806 \times 30 + 0.0113 \times 82 + 0.0220 \times 13$$

$$\hat{Y} = 1.987.$$

It is obtained that the risk level of forest fires for a temperature of 30°C, humidity of 82%, and wind speed of 13 km/h is 0.923 (low). Here is the complete calculation of the forest fire risk level using the Sugeno Fuzzy Regression model as the Table 10.

Table 10. Forest Fire Risk Level ($\hat{Y}$) Using Fuzzy Sugeno Global Regression Model

No	Temperature (℃)	Humidity (%)	Wind Speed (Km/h)	$\hat{Y}$	Category
1	30	82	13	1.987	Medium
2	30	81	12	1.954	Medium
3	31	79	13	2.534	High
4	30	80	14	1.987	Medium
5	32	75	16	3.135	High
6	32	71	17	3.112	High
7	32	72	17	3.124	High
8	32	75	16	3.135	High
9	31	78	15	2.567	High
10	32	76	15	3.135	High
11	32	76	14	3.103	High
12	32	76	14	3.103	High
13	31	77	14	2.533	High
14	31	77	13	2.511	High
15	32	75	14	3.091	High

Based on Table 10, the average level of wildfire risk is as follows.

$$\frac{\sum_{i=1}^{15} \hat{Y}_i}{15} = 68.89.$$

Therefore, the average forest fire risk level in Tanjung Puting National Park is 68.89 (high risk category).

3.5 Evaluation of the Sugeno Fuzzy Method Using Root Mean Square Error (RMSE)

In the context of the Sugeno fuzzy method, Root Mean Square Error (RMSE) is used to measure the average squared error between predictions and actual values. The RMSE value obtained is:

$$\sqrt{\frac{\sum(Y_i - \hat{Y}_i)^2}{n}} = \sqrt{\frac{3856.25}{15}} = 16.03.$$

The RMSE value of 16.03 indicates that the forest fire risk measurement model using Zero Order Fuzzy Sugeno has a low error rate from the output range (0-100), so the prediction results can be categorized as good and quite accurate for measuring the rate of forest fire risk based on the variables of temperature, humidity, and wind speed.

The obtained RMSE for the value is First Order Fuzzy Sugeno:

$$\sqrt{\frac{\sum\left(Y_i - \hat{Y}_i\right)^2}{n}} = \sqrt{\frac{3590.507}{15}} = 15.47.$$

The RMSE value of 15.47 indicates that the model for measuring forest fire risk using First Order Fuzzy Sugeno has a low error rate within the output range of 0-100; therefore, the prediction results can be categorized as good for measuring the level of forest fire risk based on the variables of temperature, humidity, and wind speed.

4. CONCLUSION

The Zero-Order Fuzzy Sugeno Method initially had a weakness in that undefined defuzzification results occurred when input values equaled the membership function boundaries. After modifying membership function limits, it produced an average forest fire risk level of 68.83 (high category) in Tanjung Puting National Park. The First Order Sugeno model is recommended for measuring forest fire risk. It has a smaller RMSE (15.47) compared to the Zero Order Sugeno model (16.03). The First Order model is more sensitive to large errors, provides more consistent and stable predictions, and is better suited for handling extreme conditions, such as surges in hazardous risk. In summary, both methods identified a high risk of forest fires in the study area, with the First Order Sugeno method showing slightly better performance in terms of accuracy and handling extreme conditions.

Author Contributions

Rani Natalia Purba: Conceptualization, Methodology, Resources, Software, Validation, Writing – original draft. Esther Sorta Mauli Nababan: Conceptualization, Methodology, Validation, Supervision, Writing – Review and Editing. Prana Ugiana: Formal Analysis, Visualisation, Writing –Improvement upon the draft and editing. Romi Syahputra: Resources, Software, Validation. Zahedi: Data Curation, Software, Investigation. All authors reviewed, discussed, and agreed on the final version of the manuscript and contributed equally to the development and completion of this research.

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Declarations

The author declares that there is no conflict of interest related to this study.

Declaration of Generative AI and AI-assisted technologies

Generative AI (ChatGPT) was used exclusively for language editing and stylistic improvement. The authors take full responsibility for the content and confirm that all analyses, results, and interpretations are their own. The final manuscript was reviewed for linguistic accuracy by an English-language expert.

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