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FUZZY LOGIC APPLICATION FOR DETERMINING THE FEASIBILITY OF NICKEL MINING IN SOUTHEAST SULAWESI PROVINCE

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ABSTRACT

This study uses the Mamdani method to assess the feasibility of nickel mining locations in Southeast Sulawesi Province. Despite the crucial role of mining in the Indonesian economy, research on the site feasibility decisions in mining using the Mamdani method still needs to be completed. Therefore, this study addresses this knowledge gap by providing new contributions and effective solutions. The Mamdani method is employed in the various stages of mining activities, particularly in feasibility studies, which are the main focus. Mining feasibility studies involve both technical and non-technical analyses, encompassing aspects such as nickel reserves and environmental impacts. This research seeks to expand the use of the Mamdani method in mining site feasibility decisions, offering sustainable and environmentally responsible solutions. The research results show that North Konawe Regency has very large estimated nickel reserves but has a relatively low environmental impact and is quite far from the port, thus achieving a high location suitability score for mining. On the other hand, Konawe Regency has lower nickel reserves but has quite a large environmental impact, and the distance to the port is quite far, so the location feasibility score is lower. The outcomes of this research are expected to provide new insights, fill knowledge gaps, and serve as a valuable reference for future mining site feasibility decision-making. The translation is accurate, well-structured, and free from plagiarism.

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1. INTRODUCTION

Mining is a crucial sector contributing significantly to Indonesia's economy [1]. The primary objective of mining activities is to harness the Earth's mineral resources for human welfare [2]. Indonesia is endowed with vast metallic mineral resources, including nickel [3]. According to data from the Ministry of Energy and Mineral Resources (ESDM) in 2020, nickel mining activities in Indonesia are distributed across several provinces, with the largest operations located in Southeast Sulawesi Province [4].

The stages in mining activities generally include general investigation, exploration, feasibility study, mine planning, construction, mining, processing and/or refining of mineral materials, marketing, and reclamation [5]. Before undertaking mine planning, it is crucial to conduct a feasibility study, which represents the final stage in determining whether mineral deposit extraction is economically viable.

The feasibility study for mining is about the Republic of Indonesia Law No. 3 of 2020 concerning mineral and coal mining. It stipulates that a feasibility study is an integral part of the stages in mining business activities, aimed at obtaining detailed information on all relevant aspects to determine mining ventures' economic and technical viability. This includes an analysis of environmental impacts and planning for post-mining activities [6]. The general feasibility investigation for mining involves a preliminary site inspection, encompassing technical and non-technical aspect [5].

Key technical aspects are associated with minerals or ore and geological processes. Meanwhile, non-technical aspects include the location of the investigation site, access to the site, and supporting infrastructure such as roads, bridges, airports, ports, markets, and other public facilities [5]. According to Bullock [7], preparing a technical feasibility report with reliable and auditable data aims to demonstrate the project's viability, making it marketable to others or sustainable while awaiting potential technological advancements or market opportunities. According to Lee [8], the three stages of economic and/or financial feasibility for a mining enterprise are conceptual study, preliminary or pre-feasibility study, and feasibility study. In this context, the use of the Mamdani method for making decisions on the feasibility of mining locations provides significant innovation, as demonstrated by Mala's research [9], which applied the Mamdani method to generate the best decisions by creating a decision support system that provides tourist recommendations. Noori's research results indicate that fuzzy logic is more accurately used to identify suitable areas for dam construction for water management in the northern regions of Iraq affected by climate change [10].

Based on the above description, this research aims to assess the feasibility of mining locations in Southeast Sulawesi Province using the Mamdani method. The use of the Mamdani method in determining the feasibility of mining locations is relatively scarce and has not been extensively researched. Therefore, this study needs to be further developed. In the context of this research, applying the Mamdani method is expected to provide new contributions and more effective solutions in determining the feasibility of appropriate mining locations based on relevant criteria, such as nickel reserves, environmental impact, and access to ports. Thus, this research is expected to fill existing knowledge gaps, provide new insights, and have the potential to serve as a reference for industry practices in environmentally sustainable and responsible mining location decision-making.

2. RESEARCH METHODS

Fuzzy Logic, as one of the algorithms at the forefront of artificial intelligence, is not limited solely to its applications in medicine and economics. It is also found in various scientific disciplines, including mining. In general, fuzzy logic is employed to address issues involving uncertainty, and reasoning methods such as Tsukomoto, Mamdani, and Sugeno have been elucidated by Jayanti & Hartati [11].

This research delves explicitly into applying Fuzzy Logic using the Mamdani method in mining feasibility in the Southeast Sulawesi Province. The processed data involve criteria for mining feasibility, such as nickel reserves, environmental impact, and accessibility (distance to the port), to accurately determine mining locations that can be categorized as feasible. Nickel reserves refer to the amount of nickel that can be economically extracted from the earth's crust or known or estimated nickel mine deposits. Water pollution at mine sites is often considered a significant environmental impact due to the potential for extensive and long-term damage to water ecosystems, human health, and the well-being of local communities. The distance of the mine site to the port is an important criterion in evaluating the feasibility of a mine. Optimal distance will support operational efficiency, reduce transportation costs, and reduce logistics risks, thereby increasing potential profits from mining exploitation. This data is sourced from various outlets in accordance with the established criteria [12], [13], [14], [15], [16], [17] and the analytical results are comprehensively presented in Table 1.

Table 1. The Input Variables (Nickel Reserves, Environmental Impact, and Accessibility)

Location	Nickel Reserves (billion Weight Metric Ton)	Environmental impact (water pollution index)	Accessibility/distance to Port (Km)
Konawe Regency	1.58	6.30	69.5
Kolaka Regency	12.82	2.12	16.6
South Konawe Regency	4.35	2.82	108
Bombana Regency	28.20	2.91	5.5
North Kolaka Regency	2.76	2.12	14.4
North Konawe Regency	46.00	2.06	69
Buton and Baubau Regency	1.68	2.71	26.5

Data Source: Southeast Sulawesi Bappeda [12], *Google Maps*

The Mamdani method, also known as the MIN-MAX method, was introduced by Ebrahim Mamdani in 1975. This method involves four crucial stages to generate the desired output. The Mamdani fuzzy inference system (FIS) is grounded in a highly formal insight into the structure of categories and articulated "IF-THEN" fuzzy rules that can be based on expert knowledge [18]. General steps are necessary for the application of a fuzzy model (see Figure 1): (1) Input and output variables are fuzzified by considering convenient linguistic subsets; (2) Rules that relate input to output are constructed based on expert knowledge and/or extracted from data samples; (3) A reasoning mechanism is used to apply the rules to each input, resulting in a compound fuzzy set generated by the logical union of two or more fuzzy membership functions defined on the universe of discourse of the output variable; (4) A defuzzification procedure is performed to convert the fuzzy output to a crisp number [18].

In the first stage, fuzzification is changing crisp input into fuzzy input based on the role of linguistic variable membership functions. The first step is to determine each linguistic value's membership function. The input variables chosen are three domains of nickel mining: location feasibility seen from nickel reserves, environmental impact, and accessibility. The values in each domain will be a clear input of each variable. Because the output variable is the feasibility of nickel mining locations, the sharp output is the feasibility value of each district in Southeast Sulawesi province. The fuzzy set of each input variable uses a triangular membership function approach, as shown in Table 2, and the fuzzy set of output variables uses a trapezoidal membership function approach.

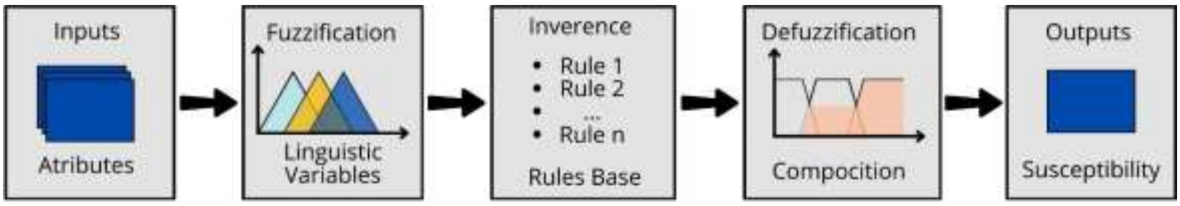

Figure 1. Scheme of the general FIS structure. Based on Lucchese

2.1 Fuzzification

Fuzzification is the stage where crisp input values are transformed into fuzzy values [19]. In the Mamdani method's formation of fuzzy sets, input, and output variables are divided into fuzzy sets with multiple linguistic values describing their characteristics. Membership functions (MF) for each input and output variable must be defined to determine the membership degree (MD) for each antecedent fuzzy rule. The MF is assigned to the corresponding linguistic fuzzy set. The chosen input variables are the three criteria domains for mining location feasibility: nickel reserves, environmental impact, and accessibility (distance to the Port). As the output variable is the feasibility of mining locations, the crisp output represents the feasibility value for each district in Southeast Sulawesi Province. The fuzzy sets for each variable use a triangular membership function approach, as shown in Table 2.

Tabel 2. Fuzzy Set Input and Output

	Variable	Fuzzy Sets	Universal Set	Domain
Input	Nickel Reserves	Few	[1.58 – 46.00]	1.58 – 23.79
		Medium		1.58 – 46.00
		Many		23.79 – 46.00
	Environmental Impact	Low	[2.06 – 6.30]	2.06 – 4.18
		Medium		2.06 – 6.30
		Hight		4.18 – 6.30
	Accessibility	Near	[5.5 – 108]	5.5 – 56.75
		Medium		5.5 – 108
		Far		56.75– 108
Output	Location Feasibility	Not feasible	[0 – 10]	0 – 4
		Less feasible		2 – 8
		Feasible		6– 10

2.2 Application of Implication Functions

Applying implication functions involves establishing inference rules through IF-THEN statements based on input and output variables. These rules play a crucial role in supporting the Fuzzy Inference System (FIS), which is responsible for evaluating sharp inputs and converting them into fuzzy input values using the Min (Minimum) implication function. The rule base of the Mamdani fuzzy system, with n inputs, m outputs, and k rules, can be represented according to the following Equation (1) [20]:

$$R_i: IF(x_1\ is\ f_{i,1})AND\ (x_j\ is\ f_{i,j})\ AND\ ...(x_n\ is\ f_{i,n})\ THEN\ (y_i\ is\ g_i). \quad (1)$$

2.3 Composition of Rules

Based on expert knowledge or available data, fuzzy rules are established, creating connections between the subsets of input and output variables. The system's rule composition involves multiple rules forming relationships. Consequently, inference is obtained through the combination of rules. There are three methods available for use in the Fuzzy Inference System: Max, Additive, and Probabilistic OR.

2.4 Defuzzification

Defuzzification strives to derive crisp values from fuzzy output to obtain a singular crisp output value. The Mamdani approach employs five defuzzification techniques: centroid of area, bisector, mean of maximum, greatest of maximum, and smallest of maximum. Equation (2) provides the general formula for the centroid of area method.

$$z = \frac{\int_z \mu(z)z dz}{\int_z \mu(z) dz} \quad (2)$$

3. RESULTS AND DISCUSSION

A fuzzy logic designer in Matlab supports the Fuzzy Inference System (FIS). This formation consists of three input variables (nickel reserves, environmental impact, and accessibility) and one output variable (feasibility of the mining location). The configuration of input and output variables in the formation of fuzzy logic is illustrated in Figure 1.

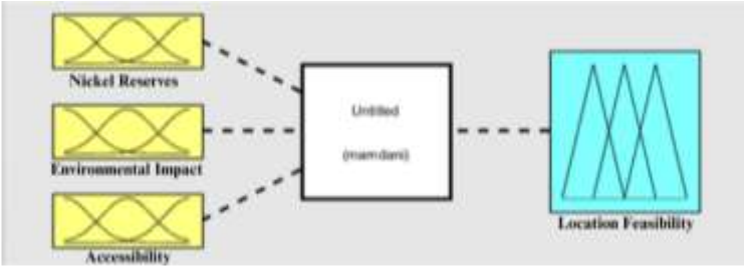

Figure 2. Input and Output Formation of Fuzzy Logic with Matlab

Figure 2 shows 3 inputs used, namely nickel reserves, environmental impact, and accessibility, while there is one output, namely mine location feasibility.

3.1 Fuzzification

Creating fuzzy sets, also called the fuzzification process, involves transforming input data with definite values into input in the form of degrees of membership in fuzzy sets. The implementation design is carried out using Matlab R2016a software, which will serve as the system for determining the predicted data on the feasibility of mining location values. The membership functions of each input and output variable are illustrated as follows:

The design of the nickel reserve input is shown in Figure 3.

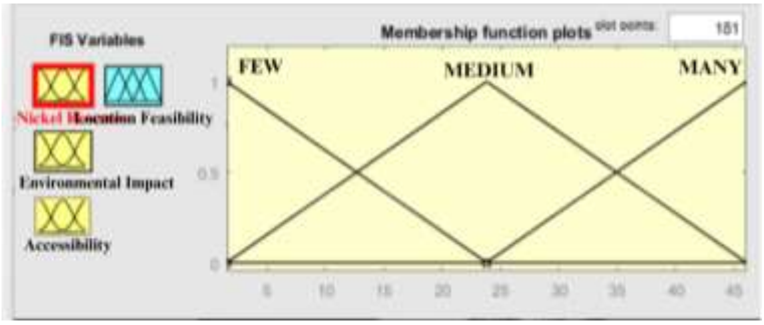

Figure 3. Nickel Reserve Input Variable Translation

Figure 3 shows 3 fuzzy sets in the nickel reserves variable, namely FEW, MEDIUM, and MANY. The nickel reserve variable membership function equation is expressed using Equation (3), Equation (4), and Equation (5).

$$\mu_{Few}[\text{x, 1.58, 23,79}] = \begin{cases} 1, & x < 1.58 \\ \frac{23.79-x}{22.21}, & 1.58 \le x \le 23.79 \\ 0, & x > 23.79 \end{cases} \quad (3)$$

$$\mu_{Medium}[x, 1.58, 23.79, 46.00] = \begin{cases} 0; & x < 1.58 \; atau \; x > 46.00 \\ \frac{x-1.58}{22.21}; & 1.58 \le x \le 23.79 \\ \frac{46.00-x}{22.21}; & 23.79 \le x \le 46.00 \end{cases} \quad (4)$$

$$\mu_{Many}[x, 23.79, 46] = \begin{cases} 0, & x < 23.79 \\ \frac{x-23.79}{22.21}, & 23.79 \le x \le 46.00 \\ 1, & x > 46.00 \end{cases} \quad (5)$$

The design of the environmental impact input is shown in Figure 4.

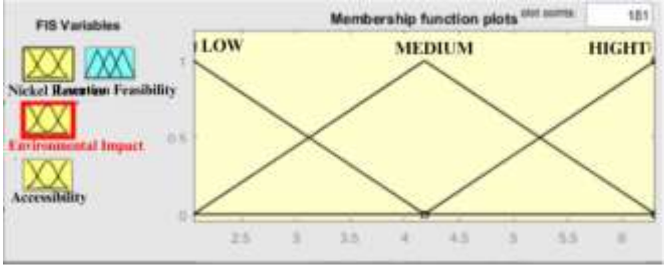

Figure 4. Environmental Impact Input Variable

Figure 4 shows 3 fuzzy sets of environmental impact variables, namely LOW, MEDIUM, and HIGHT. The membership function equation for environmental impact variables is expressed using **Equation (6)**, **Equation (7)**, and **Equation (8)**.

$$\mu_{Low}[x, 2.06, 4.18] = \begin{cases} 1, & x < 2.06 \\ \frac{4.18-x}{2.12}, & 2.06 \leq x \leq 4.18 \\ 0, & x > 4.18 \end{cases} \tag{6}$$

$$\mu_{Medium}[x, 2.06, 4.18, 6.30] = \begin{cases} 0; & x < 2.06 \; or \; x > 6.30 \\ \frac{x-2.06}{2.12}; & 2.06 \leq x \leq 4.18 \\ \frac{6.30-x}{2.12}; & 4.18 \leq x \leq 6.30 \end{cases} \tag{7}$$

$$\mu_{Hight}[x, 4.18, 6.30] = \begin{cases} 0, & x \leq 4.18 \\ \frac{x-4.18}{2.12}, & 4.18 \leq x \leq 6.30 \\ 1, & x \geq 6.30 \end{cases} \tag{8}$$

The design of the accessibility input is shown in **Figure 5**.

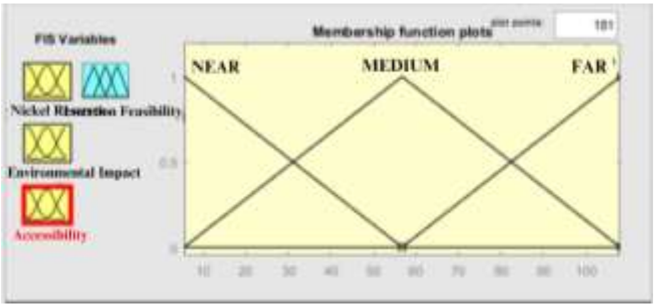

Figure 5. Accessibility Input Variable

Figure 5 shows 3 fuzzy sets of accessibility variables, namely NEAR, MEDIUM, and FAR. The membership function equation for the accessibility variable is expressed using **Equation (9)**, **Equation (10),** and **Equation (11)**.

$$\mu_{Near}[x, 5.5, 56.75] = \begin{cases} 1, & x < 5.5 \\ \frac{56.75-x}{51.25}, & 5.5 \leq x \leq 56.75 \\ 0, & x > 56.75 \end{cases} \tag{9}$$

$$\mu_{Medium}[x, 5.5, 56.75, 108] = \begin{cases} 0; & x < 5.5 \; atau \; x > 56.75 \\ \frac{x-5.5}{51.25}; & 5.5 \leq x \leq 56.75 \\ \frac{108-x}{51.25}; & 56.75 \leq x \leq 108 \end{cases} \tag{10}$$

$$\mu_{Far}[x, 56.75, 108] = \begin{cases} 0, & x < 56.75 \\ \frac{x-56.75}{51.25}, & 56.75 \leq x \leq 108 \\ 1, & x > 108 \end{cases} \tag{11}$$

The design of the mining location feasibility output is shown in **Figure 6**.

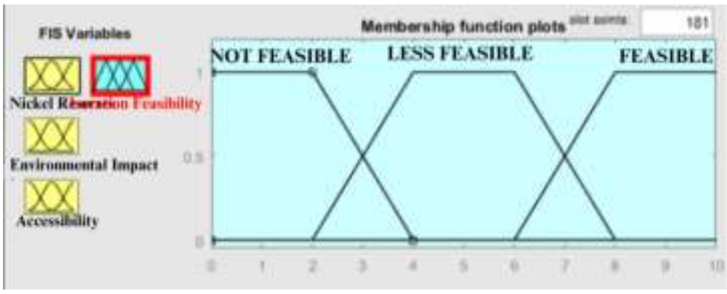

Figure 6. Output Variable Mining Location Feasibility

Figure 6 shows 3 fuzzy sets of mining location feasibility variables, namely NOT FEASIBLE, LESS FEASIBLE, and FEASIBLE. The membership function equation for the mine location feasibility variable is expressed using **Equation (12), Equation (13),** and **Equation (14)**.

$$\mu_{Not\ Feasible}[y,\ 0,\ 2,\ 4] = \begin{cases} 1; & 0 < y < 2 \\ \frac{4-y}{2}; & 2 \le y \le 4 \\ 0; & y > 4 \end{cases} \quad (12)$$

$$\mu_{Less\ Feasible}[y,\ 2,4,6,8] = \begin{cases} 0: & y < 2 \\ \frac{y-2}{2}, & 2 \le y \le 4 \\ 1; & 4 \le y \le 6 \\ \frac{8-y}{2}, & 6 \le y \le 8 \\ 0; & y > 8 \end{cases} \quad (13)$$

$$\mu_{Feasible}[y,\ 6,8,10] = \begin{cases} 0; & y < 6 \\ \frac{y-6}{2}; & 6 \le y \le 8 \\ 1; & 8 < y > 10 \end{cases} \quad (14)$$

3.2 Application of Implication Functions

The Min implication function uses the AND operator on the antecedents of the rule, determining the intersection of two or more fuzzy sets on the antecedents and the consequences of the rule. The antecedent contains input variables, while the result of the rule contains the output variable. Based on the number of fuzzy sets formed for each input and output variable, the total number of rules to be determined is 27 fuzzy set rules. The formed regulations are presented in Figure **Figure 7**.

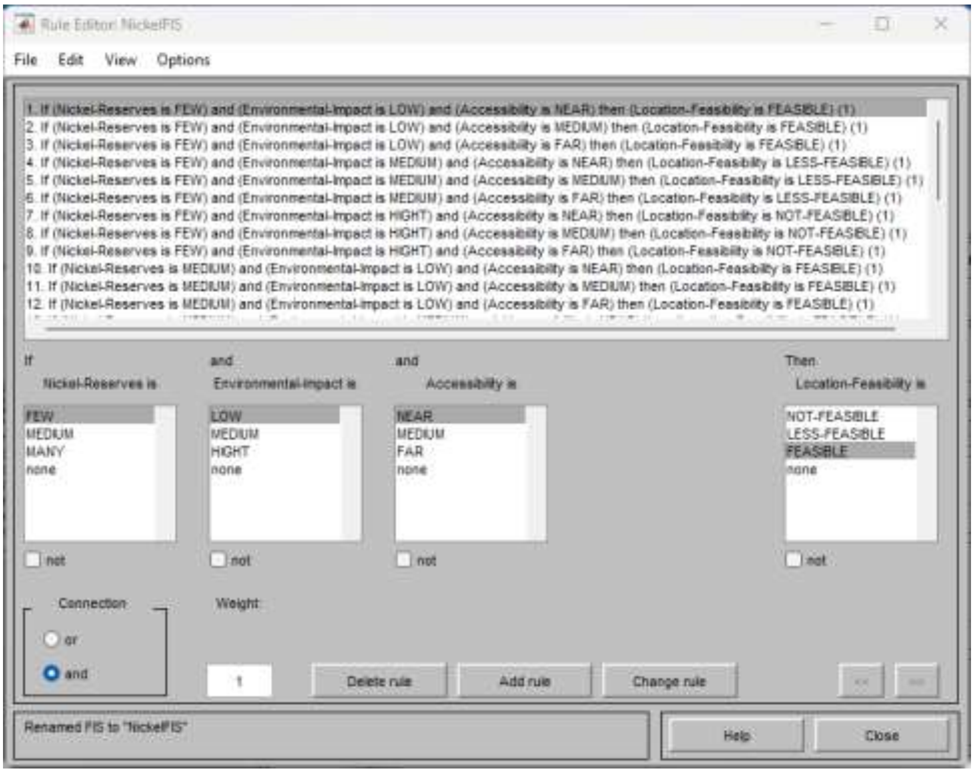

Figure 7. Fuzzy Rules from Matlab

The fuzzy rule image above shows the relationship between input variables (nickel reserves, environmental impact, and accessibility) and output variables (mine location feasibility). These rules are used in fuzzy control systems to determine the system response to given input conditions. For example, rule number 1 states that if the nickel reserves variable has a "FEW" value, the environmental impact variable has a "low" value. Accessibility has a "NEAR" value, then the output variable will have a "FEASIBLE" value. These rules are used as a guide in regulating system actions according to given conditions. Based on Figure 7, the fuzzy rules formed are presented clearly in Table 3.

Table 3. Fuzzy Rules

Rule Number	Nickel Reserves	Environmental Impact	Accessibility	Feasibility of Mining Location
[R1]	FEW	LOW	NEAR	FEASIBLE
[R2]	FEW	LOW	MEDIUM	FEASIBLE
[R3]	FEW	LOW	FAR	FEASIBLE
[R4]	FEW	MEDIUM	NEAR	LESS FEASIBLE
[R5]	FEW	MEDIUM	MEDIUM	LESS FEASIBLE
[R6]	FEW	MEDIUM	FAR	LESS FEASIBLE
[R7]	FEW	HIGHT	NEAR	NOT FEASIBLE
[R8]	FEW	HIGHT	MEDIUM	NOT FEASIBLE
[R9]	FEW	HIGHT	FAR	NOT FEASIBLE
⋮	⋮	⋮	⋮	⋮
[R26]	MANY	HIGHT	MEDIUM	LESS FEASIBLE
[R27]	MANY	HIGHT	FAR	NOT FEASIBLE

3.3 Composition of Rules

System testing was carried out after the system was developed to determine the feasibility predictions for nickel mining locations in Southeast Sulawesi Province based on criteria such as nickel reserves, environmental impact, and accessibility after the fuzzy rules were formed. For example, a mining location in the Buton and Baubau districts with nickel reserves of 1.68 Wmt, environmental impact of 2.71wpi, and access of 26.5 km. The input data for each input variable is [1.68; 2.71; 26.5] into the FIS Mamdani method built-in Matlab in the rule viewer section as in Figure 8.

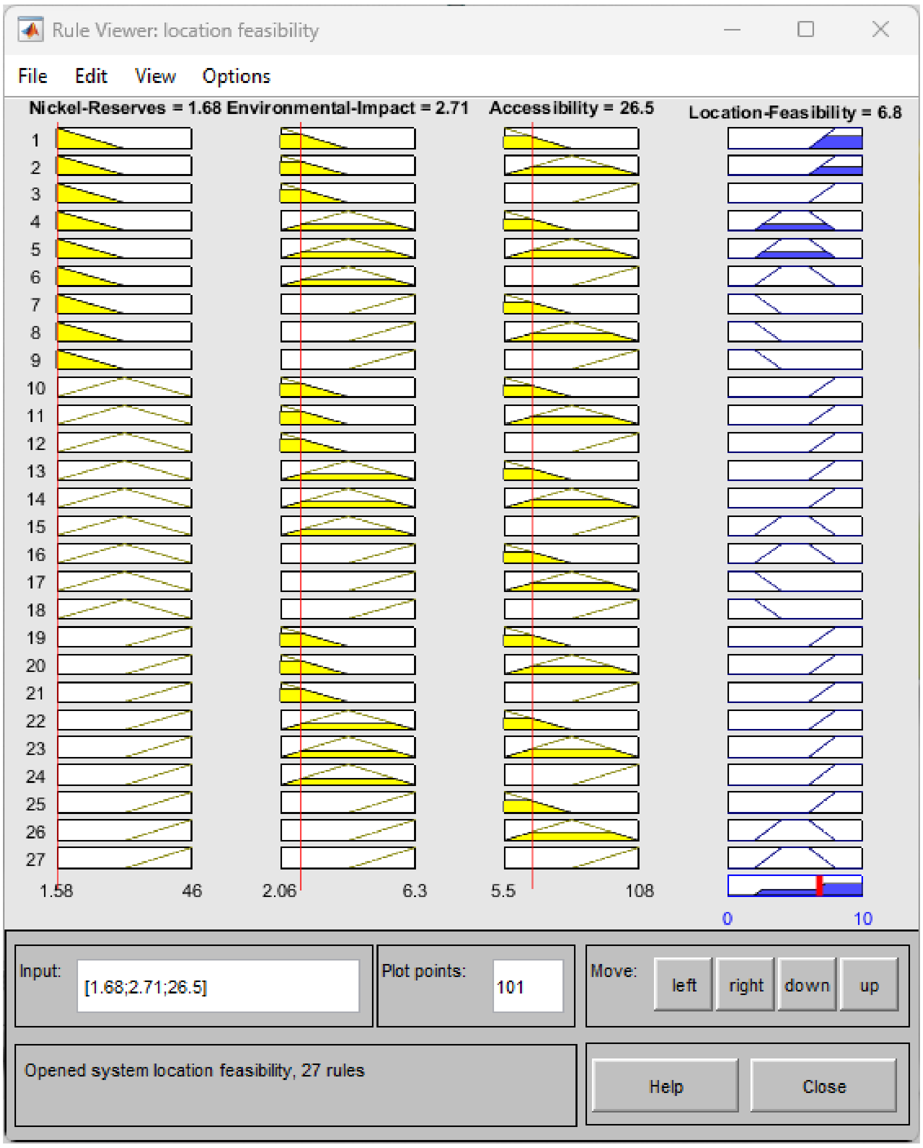

Figure 8. Inverence Rules

Based on Figure 8 above, the result of the prediction system for the feasibility of nickel mining locations in Buton and Baubau districts is 6.8.

3.4 Defuzzification

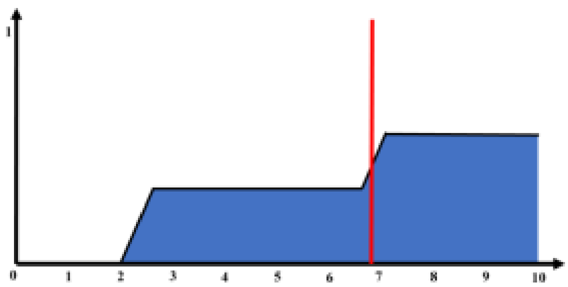

Figure 9. a fuzzy set that represents the overall conclusion for the measured value of nickel reserves, environmental impact, accessibility as well as the defuzzification value of location feasibility

The defuzzification method is the Centroid method with a continuous domain, using **Equation (2)**. So, the example shows the feasibility of nickel mining locations in the Buton and Baubau districts with nickel reserves of 1.68, an environmental impact of 2.71, and accessibility of 26.5 6.8.

3.5 Discussion

Table 4. Mine Location Feasibility Value for Each District

Location	Nickel Reserves (billion Weight Metric Ton)	Environmental impact (water pollution index)	Accessibility/distance to Port (Km)	Location Feasibility
Konawe Regency	1.58	6.30	69.5	1.63
Kolaka Regency	12.82	2.12	16.6	8.02
South Konawe Regency	4.35	2.82	108	6.75
Bombana Regency	28.20	2.91	5.5	8.31
North Kolaka Regency	2.76	2.12	14.4	8.23
North Konawe Regency	46.00	2.06	69	8.38
Buton and Baubau Regency	1.68	2.71	26.5	6.8

From **Table 4**, it can be seen that North Konawe Regency has vast estimated nickel reserves but has a relatively low environmental impact and is quite far from the port, thus achieving a high score of location suitability for mining. On the other hand, Konawe Regency has lower nickel reserves. Still, it has quite a large environmental impact, and the distance to the port is quite far. Hence, the location feasibility score is lower.

4. CONCLUSIONS

A comprehensive assessment of the feasibility of a mine site aims to ensure maximum utilization of natural resources while taking into account the consequences for the environment and society. Based on the results of research on the application of fuzzy logic to determine the feasibility of nickel mining locations in Southeast Sulawesi province, it can be concluded that the application of fuzzy logic to determine the feasibility of nickel mining using Matlab software was carried out in four stages, namely the formation of fuzzy sets; application of implication functions (rules); rule composition and defuzzification. Formation of fuzzy sets by dividing each variable into three fuzzy sets: implication function using the minimum function, rule composition using the maximum method, and defuzzification using the centroid of area method. North Konawe Regency has the highest location feasibility value with a value of 8.38, and Konawe Regency has the lowest feasibility value with a value of 1.63. Suggestions for further research include adding other input variables related to the output results and exploring different fuzzy logic that can be compared to obtain a more effective method. Furthermore, the research can be expanded by designing applications that utilize a fuzzy logic system, especially the Mamdani method, to predict the feasibility of nickel mining locations.

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