International Journal of Future Engineering Innovations

Assessment of the Risk Level of Distribution Pipelines Using the Fuzzy Logic Method Based on Risk Assessment at Pt X

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Article Info

ISSN (online): 3049-1215
Impact Factor (RSIF): 8.25
Volume: 03
Issue: 03
May-June 2026
Received: 09-03-2026
Accepted: 06-04-2026
Published: 08-05-2026
Page No: 53-57

Abstract
Pipeline risk assessment is a crucial aspect in maintaining the integrity of the pipeline system and ensuring the continued operation of the oil and gas industry. Pipeline failure can result in technical, economic, and reputational losses for a company. Therefore, a risk assessment method capable of accurately and data-drivenly describing pipeline conditions is necessary. This study aims to develop a pipeline risk assessment model using a fuzzy logic-based risk assessment approach utilizing actual inspection data.
The data used in this study include thickness, corrosion rate, remaining life, and the visual condition of the pipeline. The method used is a Mamdani-type fuzzy inference system with a membership function based on the pipeline's technical condition, a rule base structured based on relationships between variables, and a defuzzification process using the centroid method to generate a Probability of Failure (PoF) value on a scale of 0 to 100. The PoF value is then combined with the Consequence of Failure (CoF) to obtain a risk score.
The results showed that the PoF value was able to represent the condition of the distribution pipeline in stages. High PoF values were generated by segments with low thickness, high corrosion rates, short remaining life, and poor visual condition. The CoF value was 3, derived from four parameters: population safety, affected infrastructure and environment, business loss, and company reputation. The analysis results were categorized as low. Therefore, variations in risk values were primarily influenced by the PoF value. The risk distribution showed that approximately 74.83% of distribution pipeline segments were in the low-risk category, 18.18% in the medium-risk category, and 6.99% in the high-risk category. High-risk segments were identified as critical areas requiring priority monitoring, inspection, maintenance, and prevention.
This research demonstrated that the fuzzy logic approach yields more flexible and realistic risk assessments than conventional methods and can be used as a basis for more effective, data-driven technical decision-making in the management and maintenance of distribution pipelines.

DOI: https://doi.org/10.54660/IJFEI.2026.3.3.53-57

Keywords: Distribution Pipe, risk assessment, logika fuzzy, probability of failure, consequence of failure, pipeline integrity

1. Introduction

Pipeline systems are a key infrastructure in the energy industry, particularly oil and gas, serving to transport fluids from production sources to processing and distribution facilities. The reliability of pipelines significantly impacts a company's operational continuity, safety, and economic performance. Pipeline failures can lead to leaks, environmental pollution, operational disruptions, and significant financial losses [2, 1]. Furthermore, these failures can also erode public trust and impact

a company's reputation [12].
Over time, pipelines degrade due to various factors, such as corrosion, operating pressure, environmental conditions, and service life. Among these factors, corrosion is a major cause of failure because it causes a decrease in pipe wall thickness and weakens structural integrity [14]. Inspection data such as thickness, corrosion rate, remaining life, and visual condition are important indicators in assessing pipeline condition [7]. However, processing this data into comprehensive risk indicators remains a challenge [6].
This study aims to develop a risk assessment model for pipelines using a fuzzy logic approach based on risk assessment. Specifically, the objectives of this study are to develop a fuzzy logic model using the variables of thickness, corrosion rate, remaining life, and visual condition, to calculate the Probability of Failure (PoF) value using a fuzzy inference system, to determine the risk value based on the combination of PoF and Consequence of Failure (CoF), and to identify pipeline segments with a high risk level.
Conventional risk assessment methods generally use a deterministic approach with rigid threshold values. This approach tends to classify pipeline conditions strictly into specific categories, such as safe or unsafe [17]. In reality, pipeline conditions change gradually, making this approach less able to capture the transitional conditions and uncertainties inherent in inspection data [10]. Furthermore, conventional methods often struggle to integrate multiple inspection parameters simultaneously. For example, parameters such as thickness, corrosion rate, remaining life, and visual condition are interrelated but are often analyzed separately [19]. This can lead to inaccurate risk assessment results and suboptimal decision-making support [13].
Various methods have been developed to assess pipeline risks. The Risk-Based Inspection (RBI) approach is widely used to determine inspection intervals and maintenance priorities [16]. Furthermore, probabilistic models are used to estimate the probability of failure based on statistical data [8]. Other methods such as Failure Mode and Effect Analysis (FMEA) and Bayesian Networks have also been applied to analyze risk scenarios [5].
In several recent studies, fuzzy logic has begun to be used as an alternative due to its ability to handle uncertainty and linguistic variables [9], [15]. Fuzzy-based models have been applied in inspection planning and maintenance strategy evaluation [3]. This approach allows for gradual condition classification and is more in line with real-world conditions [4].
However, most studies still use general assumptions or limited data. Some models focus more on theoretical development without integrating detailed inspection data [11]. In addition, the relationship between fuzzy-based Probability of Failure (PoF) results and practical risk assessment frameworks has not been widely discussed [18].

2. Literatur Review
2.1. Probability of Failure (PoF)
Probability of Failure (PoF) is a parameter used to describe the likelihood of failure in a pipeline due to material degradation or other operational factors. Determination of the PoF value is generally based on technical parameters such as thickness, corrosion rate, remaining life, and the visual condition of the pipeline [8].
Research by J. K. Seo *et al*. shows that corrosion parameters and material thickness significantly influence the likelihood of pipeline failure [8]. Furthermore, the corrosion rate is used to determine the rate of material degradation, while the remaining life is used to estimate the remaining operational life of the pipeline. The combination of these parameters can provide a more comprehensive picture of the actual condition of the pipeline.

2.2. Consequence of Failure (CoF)
Consequence of Failure (CoF) is a parameter used to assess the impact of a pipeline failure. This impact can include human safety, the environment, economic losses, or company reputation [1].
In the RBI approach, the CoF value is used in conjunction with the PoF to determine the risk level of a piping system. The greater the impact, the higher the resulting CoF value. Therefore, CoF evaluation is a critical component in determining inspection priorities and risk mitigation strategies.

2.3. Fuzzy Logic in Risk Assessment
Fuzzy logic is a method developed to handle uncertainty and linguistic variables in the decision-making process. The concept of fuzzy logic was first introduced by Lotfi A. Zadeh through the theory of fuzzy sets, which allows a value to have degrees of membership in more than one category [9].
In engineering, fuzzy logic is widely used because it can represent real-world conditions that are gradual and uncertain. Research by M. Singh and T. Markeset shows that fuzzy logic can be used in risk-based inspection planning to increase the flexibility of pipeline condition assessments [10]. Furthermore, research by A. Azadeh *et al.* also shows that a Fuzzy Inference System can integrate various risk parameters simultaneously and produce more realistic assessments than conventional methods [9].

3. Methods
3.1. Research Object
This research was conducted at PT X, one of the contractors under the control of the Special Task Force for Oil and Gas (SKK MIGAS) which carries out oil and gas exploration activities in Papua.

3.2. Research Design
This research uses a quantitative approach with a fuzzy logic-based modeling method to assess the risk of pipelines. The developed model aims to convert technical inspection data into Probability of Failure (PoF) values, which are then combined with Consequence of Failure (CoF) to generate a risk value.

The research process consists of:
a. Inspection data collection
b. Determining variables and membership functions
c. Developing a rule base
d. Fuzzy inference process
e. Defuzzification to obtain PoF
f. Calculating CoF
g. Risk calculation using a combination of PoF and CoF

3.3. Research Data
The data used in this study is actual inspection data for the distribution pipes, consisting of:
a. Thickness (mm) is the result of measuring the thickness of the distribution pipe material using Ultrasonic Testing

(UT).
b. Corrosion Rate (mm/year) is the corrosion rate calculated from the inspection data.
c. Remaining Life (years) is the estimated remaining life of the distribution pipe.
d. Visual Condition is the visual condition based on field inspections.

3.4. Variable Probability of Failure (PoF)
The PoF is formed from four main variables:
a. Thickness → an indicator of the physical condition of the pipe
b. Corrosion Rate → an indicator of the rate of degradation
c. Remaining Life → an indicator of the time to failure
d. Visual Condition → an indicator of the surface condition

3.5. Variable Consequence of Failure (CoF)
The CoF is determined based on the following impact parameters:
a. Impact on population
b. Impact on the environment
c. Economic impact
d. Reputational impact

3.6. Fuzzy Logic Model
3.6.1. Membership Functions
Each input variable is modeled using a membership function of the form:
a. Low
b. Medium
c. High

Membership functions are used to convert numeric values into linguistic values.

3.6.2. Rule Base
The rule base is structured based on the relationships between variables, with the format:
IF (Low Thickness) AND (High CR) AND (Short RL) AND (Poor Visual) THEN High PoF

3.6.3. Inference Systems
The model uses the Mamdani Fuzzy Inference System method, with the following stages:
a. Input fuzzification
b. Rule evaluation
c. Output aggregation

3.6.4. Defuzzification
Defuzzification is done using the centroid method, with the equation:

$$PoF=\mu x \cdot x,dx \mu x,dx$$

The defuzzification results are in the form of PoF values in the range:

$$0 \leq PoF \leq 100$$

Calculation of Probability of Failure (PoF)
The PoF value is obtained from defuzzification and represents the probability of pipe failure.
a. 0 – 25 → low
b. 26 – 50 → medium
c. 51 – 100 → high

3.6.5. Calculation of Consequence of Failure (CoF)
The data used for the Consequence of Failure (CoF) is as follows:
a. Population safety
b. Hazard radius
c. Leak volume
d. Company reputation

3.6.6. Risk Calculation and Risk Classification
The risk value is calculated using the equation:

$$Risk = PoF \times CoF$$

3.6.7. Data analysis
The analysis is conducted by:
Calculating the corrosion rate and remaining life for each segment
a. Calculating the PoF value for each segment
b. Calculating the CoF value
c. Calculating the risk value
d. Grouping risk categories
e. Determining risk distribution
f. Identifying critical segments

4. Result and Discussion
4.1. Probability of Failure (PoF) Calculation Results
Probability of Failure (PoF) describes the likelihood of a pipeline failure due to material degradation. In this study, the PoF was constructed using a fuzzy logic approach based on four main variables.

4.2. Thickness (Thickness of the Pipe Material)
Thickness is the most fundamental parameter in assessing the integrity of a pipeline. This value indicates the actual condition of the material, which has deteriorated due to corrosion or other degradation mechanisms. The unit is millimeters (mm), and the measurement method uses Ultrasonic Testing (UT).

4.3. Corrosion Rate
The corrosion rate indicates the rate of material thickness reduction per unit of time. Units used are mm/year.
Calculation:

$$CR = tinitial\text{-}tcurrent \triangle t$$

The role in PoF is CR which describes the dynamics of degradation, not just the current condition.

4.4. Consequence of Failure (CoF) Calculation Results
From the analysis, the following results were obtained:

Table 1: Consequence of Failure (CoF) Calculation Results

Consequences of Failure	Parameter	Value
Population Security	Location Loss	1
	Score	2
Infrastructure and Environment Affected and Terdampak	Hazard Radius (m)	17.90
	Location Class	1
	Score	2
Business Loss	Volume Release (m^3)	226.45
	Score	2
Company Reputation	NPS Category	6
	Score	6
Final CoF	Total Score	3
	Category	B

4.5. Distribution of Pipeline Risk

The distribution of the risk categories of the distribution pipes is shown as follows:

Table 2: Distribution of Pipeline Risk

Kategori	Jumlah Data	Presentasi
Low	107	74,83%
Medium	26	18,18%
High	10	6,99%

This distribution indicates that the majority of pipeline segments fall into the low-risk category, meaning they are still in good operational condition.

A total of 6.99% of segments fall into the medium-high risk category, indicating that some segments are beginning to show signs of criticality and require immediate attention. Meanwhile, 18.18% of segments fall into the medium-risk category, which also requires regular monitoring and preventative measures.

4.6. Implications of Research Results

The results of this study have important implications for pipeline management, namely:

a. Helping determine inspection priorities
b. Improving maintenance efficiency
c. Supporting data-driven decision-making

By using this model, companies can focus more on high-risk segments, thereby reducing the potential for pipeline failure.

5. Conclusion

This research successfully developed a pipeline risk assessment model using a fuzzy logic approach based on inspection data. The developed model integrated thickness, corrosion rate, remaining life, and visual condition variables into a fuzzy inference system to generate a Probability of Failure (PoF) value on a continuous scale from 0 to 100.

The results showed that the PoF value was able to represent the pipeline's technical condition in a step-by-step manner and was consistent with the inspection data. Segments with low thickness, high corrosion rate, short remaining life, and poor visual condition generated high PoF values, indicating a greater likelihood of failure.

The Consequence of Failure (CoF) value was 3, which is considered low, so variations in risk values were primarily influenced by the PoF value. Risk calculations showed that 74.83% of the segments were in the low risk category, 18.18% were in the medium risk category, and 6.99% were in the high risk category.

The high risk segments were identified as critical areas requiring priority in inspection and maintenance activities. These results demonstrate that the fuzzy logic approach can provide more flexible and realistic risk assessments than conventional methods and can be used as a basis for more effective, data-driven technical decision-making.

Overall, this research contributes to the development of pipeline risk assessment methods by integrating actual inspection data and a fuzzy approach, thereby improving the accuracy of critical segment identification and supporting more efficient pipeline management.

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How to Cite This Article

Marendra B, Purnomo H, Padhil A. Assessment of the risk level of distribution pipelines using the fuzzy logic method based on risk assessment at Pt X. International Journal of Future Engineering Innovations. 2026;3(3):53-57.
doi:10.54660/IJFEI.2026.3.3.53-57.

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