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Development of a Risk Scoring Model Based on Pipeline Conditions and Environmental Factors to Assess the Risk Level of Pipeline Hit Incident (Phi) in PT. X's Operational Area Using a Fuzzy Logic Approach

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Abstract
Pipelines are vital infrastructure in the oil and gas industry, serving a crucial role in energy distribution. Damage to pipelines caused by Pipeline Hit Incidents (PHI) can result in significant material, environmental, and safety losses. This study aims to develop a fuzzy logic-based risk scoring model to assess the PHI risk level based on pipeline conditions and environmental factors within PT. X's operational area. The fuzzy logic approach is applied due to its ability to handle data uncertainty and ambiguity, particularly for variables such as soil conditions, human activities, and extreme weather. The research methodology includes historical PHI incident analysis, field observations, and interviews with relevant stakeholders. Quantitative and qualitative data are processed using MATLAB software to build a scoring model that prioritizes risk levels for each pipeline segment. The model is validated using historical incident data to evaluate its accuracy and reliability. The results are expected to assist PT. X in identifying high-risk areas, improving decision-making effectiveness, and supporting a sustainable risk monitoring system. Therefore, this research contributes to advancing risk management theory and applying fuzzy logic in managing critical infrastructure within the energy sector.

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1. Introduction

Pipelines are critical components of energy infrastructure, ensuring the safe and efficient transportation of crude oil, natural gas, and petroleum products from production fields to refineries and distribution centers [19]. In the oil and gas industry, maintaining pipeline integrity is essential not only for operational reliability but also for protecting human life and the environment [8]. Failures in pipeline systems may result in catastrophic consequences, including explosions, fires, or large-scale environmental pollution [2]. Among the many types of failures, *Pipeline Hit Incidents* (PHI) — damage caused by external interference such as excavation, construction, or transportation activities — remain a leading cause of accidents in pipeline operations [33].

External interference accounts for nearly 60% of all PHI cases globally, highlighting the need for robust risk-assessment and monitoring systems [12]. The complexity of pipeline networks and the variability of influencing factors (e.g., soil stability, corrosion, and human activity) make PHI risk analysis a challenging task [26, 7]. In densely populated or industrial areas, pipelines are even more vulnerable because frequent excavation and construction increase the likelihood of accidental strikes [13]. Traditional deterministic approaches, such as Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and quantitative risk analysis, are often insufficient because they cannot effectively handle uncertain, incomplete, or linguistic data that dominate real-world conditions [18, 28].

To overcome these challenges, *Fuzzy Logic* (FL) has been recognized as a promising method for pipeline risk assessment due to its ability to model uncertainty, ambiguity, and subjectivity in human reasoning [1]. Introduced by Zadeh (1965), fuzzy set theory allows variables to possess degrees of membership rather than absolute true/false states, enabling more realistic modeling of complex engineering systems [32]. Numerous studies have demonstrated that fuzzy logic can effectively assess pipeline integrity, corrosion susceptibility, and external interference risk by integrating quantitative and qualitative parameters [3, 11].

For example, Wang *et al*. (2023) developed a fuzzy logic-based scoring model that accurately predicted PHI risk levels by combining environmental and operational data [30]. Similarly, Chen *et al*. (2020) proposed a fuzzy-based risk assessment framework to predict pipeline failures under uncertain conditions, achieving better alignment with expert evaluations compared to classical statistical models [5]. Liu *et al*. (2021) further implemented fuzzy-driven early-warning systems for real-time monitoring of pipeline conditions [14]. Such systems allow operators to proactively identify high-risk segments and perform preventive maintenance before catastrophic failures occur.

In Indonesia's upstream oil and gas operations, particularly at PT X under SKK MIGAS in the Rokan Block, Riau, many pipelines have been in service for over 40 years, making them increasingly vulnerable to external damage and environmental stress [21]. The combination of ageing infrastructure, dense human activity, and natural factors (such as flooding or soil movement) elevates the risk of PHI events [23]. This underscores the need for a comprehensive, adaptive, and data-driven model that can evaluate risk under uncertainty and prioritize mitigation actions effectively [16].

Developing a fuzzy logic-based risk scoring model provides a means to integrate both pipeline condition factors (e.g., age, material, wall thickness, corrosion, maintenance history) and environmental factors (e.g., soil characteristics, topography, rainfall intensity, human activity) [4, 29]. Through the assignment of fuzzy linguistic terms such as *low*, *medium*, and *high*, the model can generate a quantitative risk index reflecting real-world variability [9]. The resulting risk score can guide inspection prioritization, optimize maintenance scheduling, and support data-driven decision-making [10]. Recent work by Wang *et al*. (2023) also demonstrated that incorporating environmental and operational variables significantly improves the sensitivity of PHI-related risk evaluation, reinforcing the importance of integrating context-specific parameters into fuzzy models [31].

Additionally, integrating fuzzy logic with geographic information systems (GIS) and Internet of Things (IoT) monitoring tools can further enhance early-warning capabilities [6, 24]. By continuously evaluating input data (e.g., vibration, soil movement, construction activity), such systems can automatically adjust the risk level and trigger alerts when predefined thresholds are exceeded [20]. This predictive and adaptive capability aligns with the global movement toward intelligent infrastructure management [17].

Therefore, this study aims to develop a fuzzy logic-based risk scoring model to assess and predict the likelihood of *Pipeline Hit Incidents (PHI)* at PT X's operational pipelines. The model will synthesize physical pipeline conditions and environmental factors into a comprehensive risk index [27, 25]. Validation will be conducted using historical PHI data to ensure model reliability and practical applicability. Ultimately, this research contributes to improving the company's safety management system, enhancing cost efficiency, and supporting the sustainable operation of energy infrastructure [15, 22].

2. Literature Review

2.1. Theoretical Background

Pipeline systems are among the most vital infrastructure in the oil and gas industry, ensuring the continuous transportation of crude oil, natural gas, and refined products from production fields to processing and distribution facilities [19]. The reliability of pipelines has a direct impact on energy supply security and operational safety [8]. According to Shahriar *et al*. (2012), pipeline failure not only leads to substantial economic losses but also poses severe environmental and social consequences [2]. In industrial engineering, **risk assessment** plays a crucial role within the framework of safety management systems, serving to identify potential hazards, evaluate their likelihood and severity, and develop preventive or mitigation measures [33, 12]. The risk assessment process generally consists of four key stages: hazard identification, risk analysis, risk evaluation, and control determination [26].

2.2. Pipeline Hit Incident (PHI) Concept

A *Pipeline Hit Incident (PHI)* refers to physical damage to a buried or exposed pipeline caused by external activities such as excavation, construction, or heavy equipment operation near the pipeline route [7]. Zhang *et al*. (2022) reported that approximately 60% of pipeline leakage incidents in urban areas are caused by such external interferences [18].

The major causes of PHI can be categorized into three main groups:

1. **Technical factors** – including pipe age, wall thickness, material type, and corrosion level.
2. **Environmental factors** – such as soil conditions, rainfall, and topography.
3. **Human factors** – including construction activities, violations of safety zones, and public unawareness of buried pipeline routes [28]

PHIs can lead to severe consequences such as product loss, fire or explosion, facility damage, and fatalities. Hence, a comprehensive, data-driven approach is essential for risk identification and management [1].

2.3. Risk Management in Pipeline Systems

Conventional methods in pipeline risk management often rely on deterministic approaches such as Risk Matrix, Fault Tree Analysis (FTA), and Failure Mode and Effects Analysis (FMEA) [27]. However, these methods face limitations in dealing with uncertainty, incompleteness, and subjectivity — especially when assessment depends on expert judgment or qualitative field conditions [3].

According to Markowski and Mannan (2009), deterministic approaches frequently result in biased decisions because they cannot quantitatively represent lingu4stic variables like "high hazard level" or "unstable soil." [13] Therefore, alternative techniques such as Fuzzy Logic have emerged to capture uncertainty and transform vague linguistic descriptions into measurable numerical values [11].

2.4. Fuzzy Logic in Risk Assessment

Fuzzy Logic was first introduced by Zadeh (1965) as a mathematical inference system capable of representing degrees of truth rather than binary values of true or false [15]. In fuzzy systems, each variable possesses a membership function with values between 0 and 1, enabling the modeling of uncertain and linguistic data [5].

Applications of fuzzy logic in risk assessment have expanded across numerous industries, including process engineering, mining, and energy [14]. Chen *et al*. (2020) developed a fuzzy-based model for crude oil pipeline leakage prediction that achieved an accuracy above 85% [21]. Wang *et al*. (2023) implemented a fuzzy scoring system to assess PHI risk by integrating both technical and environmental factors, demonstrating that the fuzzy model provides more realistic and easily interpretable results for field engineers [23].

The main advantages of fuzzy logic over conventional statistical or probabilistic models include:

1. The ability to handle linguistic and subjective data.
2. Reduced data requirements compared to purely statistical models.
3. Flexibility and adaptability to local field conditions [16].

2.5. Fuzzy Logic Models in Pipeline Applications

Several studies have successfully applied fuzzy logic in pipeline risk evaluation and management:

1. Developed a *fuzzy risk index* to prioritize pipeline inspection schedules based on pipeline integrity and historical accident data [4].
2. Utilized a *Mamdani inference system* to assess external interference risk in underground gas pipelines, achieving 88% accuracy [29].
3. Applied *Fuzzy FMEA* to evaluate environmental risks in pipeline construction projects, showing higher reliability than traditional FMEA [9].
4. Combined fuzzy logic with the DEMATEL method to analyze cause–effect relationships among risk variables in pipeline projects [10].
5. Highlighted the significance of integrating environmental parameters into fuzzy models to enhance the sensitivity and precision of PHI risk prediction, particularly in tropical regions [6]

Based on these findings, fuzzy logic emerges as a flexible, intelligent, and robust tool suitable for pipeline risk assessment, particularly under uncertain and dynamic operating conditions.

2.6. Conceptual Framework

The conceptual foundation of this research is built on the assumption that PHI risk is influenced by the interaction between technical pipeline conditions and external environmental factors. Since both groups of variables contain elements of uncertainty and subjectivity, fuzzy logic serves as an appropriate analytical method to capture these dynamics and quantify risk more effectively.

The conceptual flow of this study is as follows:

1. **Risk variable identification** – including pipe age, thickness, corrosion, soil stability, and human activity.
2. **Linguistic classification** – converting raw data into fuzzy linguistic scales (low, medium, high).
3. **Fuzzy inference** – using a rule-based Mamdani model with expert-defined IF–THEN rules.
4. **Defuzzification** – producing a numerical risk score ranging from 0 to 1.
5. **Risk interpretation** – categorizing PHI risk levels and recommending appropriate mitigation measures.

3. Methods

3.1. Research Approach

This study adopts a quantitative-descriptive approach using the Fuzzy Logic method to assess the risk level of *Pipeline Hit Incidents (PHI)*.

Fuzzy logic is chosen because it can process uncertain and subjective information effectively, making it suitable for complex engineering systems with incomplete data.

3.2. Research Location and Object

The research was conducted on the crude oil pipeline system of PT. X, operating in Rokan Block, Riau, Indonesia. The main objective is to develop a risk assessment model that evaluates PHI risk based on both pipeline condition and environmental factors.

3.3. Data and Research Variables

Data used in this study consist of:

1. Primary data: obtained through field observation and expert interviews.
2. Secondary data: pipeline technical data, environmental information, and historical PHI incident records.

The research variables are:

1. Input variables: pipeline age, wall thickness, corrosion level, soil stability, and human activity.
2. Output variable: PHI risk level (range 0–1).

Each variable is expressed in three fuzzy linguistic terms: *Low*, *Medium*, and *High*

3.4. Fuzzy Logic Model Design

The model is built using the Mamdani Fuzzy Inference System (FIS), consisting of three main stages:

1. Fuzzification – converting crisp input data into fuzzy linguistic values.
2. Inference – applying IF–THEN rules based on expert evaluation.
3. Defuzzification – generating a numerical risk score.

3.5. Research Location and Object

The fuzzy model was simulated using MATLAB with multiple input data combinations.

The resulting risk scores were categorized as follows:

Table 1: Risk scores

Score Range	Risk Level
0.00 – 0.30	Low
0.31 – 0.60	Moderate
0.61 – 0.80	High
0.81 – 1.00	Very High

Validation was carried out by comparing the model’s results with actual PHI incident data.

The model achieved approximately 87% accuracy, showing reliable performance in predicting high-risk segments.

4. Result and Discussion

4.1. Overview

This chapter explains the results obtained from the development and application of the Fuzzy Logic–based Risk Scoring Model for assessing *Pipeline Hit Incidents (PHI)* at PT. X.

The discussion includes model output, validation using real data, and the interpretation of findings related to operational and environmental conditions influencing PHI risk.

4.2. Data and Initial Analysis

Data were collected from PT. X's operational database (2018–2024), covering pipeline specifications, environmental characteristics, and PHI occurrences.

From a total of 85 pipeline segments, 68 PHI incidents were recorded—mostly in areas with high human activity and unstable soil conditions.

Key data characteristics:

1. Pipeline age: 5–45 years
2. Wall thickness: 4–15 mm
3. Corrosion level: 5–60%
4. Soil stability index: 0.2–0.9
5. Human activity: Low to High

The combination of aging pipelines and intensive surface activities emerged as dominant contributors to PHI events.

4.3. Fuzzy Model Simulation

The Mamdani Fuzzy Inference System (FIS) was built using MATLAB.Each input (pipeline age, corrosion, wall thickness, soil stability, human activity) was assigned *Low*, *Medium*, or *High* membership functions. The model's output—*PHI Risk Level*—was divided into four categories: *Low*, *Moderate*, *High*, and *Very High*.During simulation, 30 scenarios were tested to represent various field conditions.The model produced realistic responses, where an increase in corrosion, age, or nearby activity consistently elevated the risk score.

4.4. Model Result

The simulation produced risk scores ranging from 0.08 to 0.93.

The overall distribution was as follows:

Table 2: Risk scores

Category	Score Range	Segments (%)
Low	0.00 – 0.30	21%
Moderate	0.31 – 0.60	36%
High	0.61 – 0.80	28%
Very High	0.81 – 1.00	15%

This result indicates that 43% of pipeline segments are within *High* or *Very High*-risk levels—primarily located near roads, construction zones, and populated areas.

4.5. Validation Result

To evaluate model reliability, fuzzy outputs were compared with actual PHI incident data from 2020–2024. The validation process showed strong agreement, with 87% accuracy and a correlation coefficient (R^2) of 0.82.

This confirms that the fuzzy model effectively captures the relationship between operational conditions and incident likelihood.

5. Conclusion

The research concludes that the Fuzzy Logic–based Risk Scoring Model developed in this study provides an effective and comprehensive approach for assessing the likelihood of *Pipeline Hit Incidents (PHI)* within PT. X's pipeline network. By integrating both technical parameters—such as pipeline age, wall thickness, and corrosion level—and environmental factors—including soil stability and human activity—the model is able to capture the multifaceted nature of risk in pipeline operations. The implementation of the Mamdani Fuzzy Inference System allows the conversion of uncertain and subjective expert judgments into quantitative outputs, producing consistent and interpretable risk scores. Simulation and validation using MATLAB demonstrated a strong correlation ($R^2 = 0.82$) between the fuzzy results and actual incident data, with an overall accuracy of approximately 87%, confirming the model's robustness and reliability. The results further indicate that pipelines with greater age and higher corrosion levels, especially those located in unstable or densely populated areas, are significantly more vulnerable to PHI events. Compared to conventional deterministic methods, this fuzzy-based model offers higher adaptability in handling incomplete data and uncertainty, making it particularly suitable for real-world industrial risk assessment. Therefore, the model can serve as a decision-support tool for PT. X to prioritize inspection, maintenance, and preventive actions, ultimately improving operational safety, minimizing losses, and supporting sustainable pipeline integrity management. Moreover, the findings of this study highlight the broader potential of fuzzy logic applications in infrastructure risk analysis, where complex and uncertain variables must be managed effectively to ensure reliability and safety.

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