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Fuzzy Inference System Modeling for Corrosion Risk Management of Natural Gas Pipelines

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ABSTRACT

Due to the complexity of operating conditions, predicting corrosion in natural gas pipelines is a challenge, and therefore its use in the gas industry is problematic. So, the present study employs corrosion risk management in control systems and decision prediction with fuzzy inference systems to address the uncertain phenomena of critical factors affecting natural gas pipelines. In the study, 84 factors were derived and 14 critical factors were identified using the Lawshe approach. The Boehm risk management framework was used and the factors were analysed in pairs in a fuzzy inference system. The probability and consequences of each factor were determined according to the API 581 standard and the weight coefficient of each factor was determined using the FUCOM method. In this study, a fuzzy inference system with two fuzzy inference subsystems was developed to comprehensively address both aspects of evaluation and response. First, the system uses the API 581 standard risk matrix to identify the risk level, followed by the risk response strategy determination through the sensitivity risk priority index chart. The results show that at the first level of the system, the highest risk was classified as severe and harsh, while at the second level of the system, the maximum output behavior occurred during the wear-out phase of the pipeline. The proposed fuzzy inference system has the potential to significantly contribute to the effective management of pipeline corrosion risk and the economic productivity of the gas industry.

1. Introduction

Natural gas, a crucial part of the energy supply chain, has seen a significant expansion of pipeline networks, which has contributed to the economic development of countries. However, this growth has also brought

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challenges to pipeline safety and reliability [22]. The International Energy Agency (IEA) predicts that demand for natural gas will continue to grow for several decades, leading to an increase in the total length of pipelines [31].

Corrosion is a natural phenomenon that affects the reliability of pipelines and can lead to natural gas leaks, resulting in a chain of flammable gasses, fires, and explosions. Natural gas pipeline accidents caused by corrosion can have devastating consequences for society, the economy, and the environment. Therefore, it is essential to conduct risk assessments to understand the probability and impact of natural gas pipeline corrosion accidents and develop effective emergency planning [19]. All stakeholders are concerned with assessing and analysing risks associated with pipelines. However, the lack of a comprehensive and accurate dataset often leads to unpredictable risk assessment, exacerbating the consequences of such accidents [22]. The limited availability of public datasets on pipeline corrosion further complicates corrosion prevention [11].

Risk management includes hazard assessment, risk analysis, risk assessment, risk control, supervision and continuous improvement. As risk levels reach an endurable limit, the process will be established for supervision and continuous improvement to make sure that risk levels will be remained manageable. The whole cited processes included ranging from hazard analysis and risk documentation to continuous improvement [4]. Corrosion management refers to a risk-based approach for locating corrosion, choosing an up-to-the-minute precise tool which is able to figure out the beginning and spread a local attack of corrosion that provides an opportunity by inspected consequences for diminishing the intensity and the time of attack [10].

Corrosion management, which has been developed in recent years, is a crucial tool for making sure of safety and reliability in pipelines; nonetheless, developing in precautionary corrosion management is demanding owing to the limited availability of data in targeted pipelines and corrosion causes. Developing an active corrosion management approach, based on a forecast framework, will bring about facilitating in active maintenance strategies and improving asset management in the pipeline industry.

Several studies have conducted risk assessments based on probabilistic models, such as Petri nets, Markov chains, Monte Carlo simulations, fault trees, and Bowties [3]. However, these models are based on unrealistic assumptions and are static in nature. To address the uncertainty and ambiguity in pipeline risk assessment, the use of fuzzy set theory is recommended [22]. Fuzzy logic can play a useful role in accurate and correct risk management decision-making and systematic risk analysis using mathematical methods. Fuzzy inference system models adapt the process resulting from experience and observations to the performance of a particular system to establish management and engineering knowledge. The purpose of this expert system is to obtain and apply knowledge and inference methods to achieve a more advanced solution to difficult problems that require a significant effort from scientific experts to solve.

The results of several studies on the risk assessment of gas pipelines have relied on expert opinion rather than data [7]. In this regard, the current research focuses on modeling the fuzzy inference system for managing the corrosion risk of natural gas pipelines for the strategic capability of the gas industry. This model can be used to prevent corrosion and improve risk management processes to increase safety. The purpose of this study is to develop practical knowledge in the field of corrosion risk assessment and to guide its practical application.

The remainder of this paper is organized as follows: Section 2 presents the literature review, Section 3 explains the research methodology, Section 4 presents the numerical results of the research and the research model, and Section 5 concludes the study and makes suggestions for future work.

2. Literature review

The natural gas industry proactively deals with threats to pipelines, especially corrosion. Pipeline organizations need to make quick and cost-effective decisions regarding damaged pipelines and corrosion damage to prevent incidents from escalating into high-consequence areas. The aim of this study is to provide a comprehensive structure for managing the corrosion risk of natural gas transportation pipelines through a review of the literature. In the following sections, the studies conducted in this area are discussed:

Velázquez et al. [31] analysed the internal corrosion defects of oil and gas pipelines based on inspections. If the distribution of corrosion defect characteristics is known, historical damage data from corroded oil and gas pipelines can help to estimate risk and reliability using statistical models. This paper presents a field study on the characteristics of corrosion defect characteristics in Mexican oil and gas pipelines. The investigation revealed that the depth of corrosion damage exhibits a two-dimensional behavior. The fluid properties are crucial for the statistical description of the internal corrosion damage. The results showed that the Bayesian approach allows statistical estimation of the depth of internal corrosion defects using limited information from the pipelines.

Zhang et al. [37] investigated the characteristics of AC fault parameters and the corrosion behavior of buried gas pipelines. An internal simulation experiment was conducted to investigate the effects of AC current density and cathodic protection potential on AC corrosion. The results showed that with the same cathodic protection, a higher AC current density led to a higher dynamic AC corrosion rate. Finally, the study discussed the hazards of the AC interference corrosion mechanism.

Jiang and Dong [16] analysed the mechanism of pipeline burst failure due to corrosion considering mutual effects. Using nonlinear finite element analysis and Monte Carlo simulation, an integrated method was developed to describe the failure behavior of pipelines with random defects. The failure mechanism and reliability of the pipelines were analysed and the performance changes were discussed.

Mahmood et al. [22] have developed a hybrid fuzzy Bayesian network to optimize the risk assessment of natural gas pipelines. In this paper, a fuzzy framework based on historical event data is presented. The diagnosis revealed that pipeline materials and their service life pose a significant threat to the integrity of pipelines in the Midwestern United States. This study underscores the importance of a targeted mitigation strategy to minimize risks in the pipeline network.

Ma et al. [21] conducted a quantitative risk assessment of gas pipeline operations. They developed a 3D risk assessment model that integrates gas leakage with risk-related sensitivity and a separate 3D risk assessment model that combines visual risk factors with foreseeable risk. In addition, they introduced a quantitative expression mode for visual risks based on the radar map risk matrix method. Simulation scenarios based on field data showed that the risk assessment method of visual-olfactory integration more accurately reflects the dynamic risk level of the operation process compared to simple visual safety factor monitoring.

Zhao et al. [38] evaluated the integrated dynamic risk of gas pipeline leakage in urban areas. They considered the relationship between the probability of failure and the failure rate and used a mechanical analysis model to determine the corrosion growth model. The study indicates a general development process from pipeline failure to accidents. They then modeled and analysed the consequences of different types of accidents involving buried gas pipelines.

Bai et al. [7] presented a novel risk assessment model for natural gas pipelines using Bayesian networks and DEMATEL. This model includes a knowledge graph, DEMATEL, and a network. DEMATEL was implemented to determine complicated links within the causal network and convert it into a Bayesian network structure. The Bayesian analysis facilitates the creation of a possible causal model for gas pipeline accidents and enables the prediction of possible consequences and the optimization of risk mitigation strategies. The proposed model provides a more objective approach to improve safety management and reduce risks associated with natural gas pipelines and other digital-age facilities.

Qin et al. [27] assessed the equipment risk associated with oil and natural gas processing stations based on the thinness of pipeline walls. The researchers categorized the corrosion rates and failure consequences into five levels and developed a risk assessment matrix for the oil and gas processing station to avoid the risk assessment error caused by a mismatch in the failure database. The study concluded that the risk level of corrosion and thinning failure is moderate considering the current operational and management status of the station.

Fang et al. [11] developed machine-learning algorithms to predict the internal corrosion of natural gas pipelines. The authors simulated thousands of corrosion scenarios for crude oil and natural gas pipelines and developed two algorithms to predict the internal corrosion rate based on operating conditions. The results showed that the proposed algorithms effectively predicted the internal corrosion rates of pipelines.

Huang et al. [14] introduced a risk-based approach for pipeline corrosion inspection. The study used a dynamic Bayesian network, in-line inspection data, and corrosion knowledge to probabilistically model time-dependent pipeline failures. The researchers considered two failure scenarios (leakage and bursting) and estimated the probability of pipeline failure over time and the consequences of failure using the Monte Carlo simulation method. The authors also introduced a model for optimizing maintenance with the lowest total cost.

Woldesellasse et al. [34] used Bayesian belief network and a geographic information system (GIS) model to assess the consequences of gas pipeline corrosion. The authors proposed the integration of these two approaches to estimate the consequences of gas pipeline failure on society and the environment. The researchers employed pipe specifications, failure mode, and population density as inputs to calculate the losses. An event tree was used to represent all potential consequences of a gas release, and the social and environmental consequences of corrosion were estimated based on empirical equations and subjective judgment. The findings of this study suggest that the combination of these two approaches is an effective tool for estimating the severity of a pipe burst in a given area using the available information.

Liang et al. [20] investigated the integrated risk of polyethylene gas pipelines based on fuzzy TOPSIS and inference for urban areas. A fault tree was utilized to determine the risk status, and the results of the risk assessment of the polyethylene gas pipelines were presented in the form of an inference. The case study demonstrated that the pipeline risk was moderate and the management of time-related indicators and third-party damage was a priority.

Li et al. [19] developed a risk assessment framework that considers the uncertainty of corrosion incidents in natural gas pipelines. This approach was developed to uncover the uncertainties in the probability of failure and the impact of pipeline leakage. The identified parameters were described with a series of probability density functions. Finally, the Monte Carlo method was employed to solve the generated models. The sample of the study shows that the proposed framework is a valuable tool for the risk assessment of accidents due to corrosion of natural gas pipelines.

Raeihagh et al. [28] developed a pipeline risk assessment model using an artificial neural network and a fuzzy inference system. The fuzzy model was created using MATLAB software and the results were utilized to develop the ANN implemented in phases 9 and 10 of the South Pars gas field. The proposed model demonstrated a higher level of accuracy and reliability in assessing pipeline risks than previous approaches.

Figure 1 shows the number and geographical distribution of the relevant studies. Figure 1 has demonstrated the research gap and remind the significance of developing a risk management framework in pipeline corrosion, especially in Iran with its dry and ultra-dry climate.

Figure 1. Number and geographical distribution of the literature reviewed in this study

Due to the critical nature of pipeline integrity, various studies have been conducted to identify and assess risks, which has led to a lack of consensus regarding corrosion management. This makes it challenging to provide a comprehensive corrosion prediction system. To address this issue, it is necessary to present comprehensive results that can improve the integrity of pipelines in the oil and gas industry. The literature review has shown that the complexity of the corrosion system is due to the multitude of factors at play. Furthermore, the variety and extent of factors affecting corrosion are critical issues that need to be comprehensively identified and assessed in a timely manner. Conventional modeling and mathematical calculation methods, such as classical modeling and deterministic analysis tools, are limited in their ability to address the uncertainty of human judgments, evaluations, and decision-making. Fuzzy logic, on the other hand, is a powerful tool for dealing with uncertainty, solving problems, and reducing the influence of personal judgment on decisions. The main objective of this research is to develop a method for pipeline risk management based on a fuzzy inference system. The method used in this study to predict and evaluate the corrosion of a fuzzy inference system is a two-step process. The ambiguity of data, lack of sufficient data, and statistical extrapolation are reasons for using fuzzy logic. With the aim of comprehensively identifying the corrosion factors and risk assessment, this study aims to improve the effectiveness and efficiency of the corrosion management system through proper management of these factors.

The literature review shows there are significant concepts in gas pipelines like “risk, corrosion, management”. Corrosion causes disorders in correct function of the continuity in transferring gas and it affects the safety level of pipelines. Risk management aids the reduction in risk influences and to control; also, it prevents the occurrence of disorders in gas pipelines. Moreover, the literature review describes this subject that there is an array of capabilities in pipeline corrosion management, which enhances responding ability to risks in pipelines. In the considered literature review, there are not any frameworks which provide a comprehensive attitude in detecting, assessing and responding to risks; therefore, the current research has been conducted with the aim of completing research gaps. The framework for fuzzy inference systems is plain and well-described. Data is analysed by fussy inference systems (FIS) for adapting to better situation, following the maintenance conditions and classifying the behaviour of pipelines. A FIS based system is able to detect risks, by enabling an intelligent alarm system, to offer corrective measures with the aim of reducing costs of maintaining and repairing and protecting more adapted to external environment and more efficient pipelines. The precision and the accuracy of achieved yields brings about the reduction in costs, time and human resources for protecting and maintaining pipelines and the increase in efficiency in pipelines.

3. Methodology

This study was practical in nature and descriptive in its approach to data collection. It was conducted during the winter of 2024. The target population of the study consisted of corrosion experts. The Lawshe method was used to select a sample of 30 experts with at least 10 years of experience in the fields of engineering, materials, and metallurgy. Risk management is a systematic process that involves identifying, analysing, and responding to risks with the aim of maximizing positive consequences and minimizing negative consequences [26]. Boehm [9] describes risk management as a two-step process that includes risk assessment, i.e. identifying, analysing, and prioritizing risks, and risk control, i.e. planning and monitoring. Boehm's risk management process is shown in Figure 2. Bohem considers risk management as a two-step process of “risk assessment based on recognition, analysis and prioritizing risks” and “risk control, based on providing planning and supervision” in accordance with Figure 2 [9].

Figure 2. Boehm's risk management [9]

The first step is to identify the components and indicators of the model. After identifying the main risks, the next step is to compare and analyse the criteria in pairs and assess the frequency of occurrence and consequences based on the API 581 standard [5]. Finally, the FUCOM approach is used to determine the significance of the identified critical factors. The FUCOM technique can be implemented in three steps using a single-objective nonlinear mathematical model. In the first step, the evaluation factors based on expert opinions are ranked according to their importance. In this step, the criteria are defined from the most important to the least important. If two or more criteria have the same importance coefficient, an equal sign is used between them [25].

$$C_j(1)>C_j(2)>\ldots>C_j(k) \tag{1}$$

In the second step of the process, a comparative analysis is performed to assess the relative merits of the $C_j(k)$ criterion versus the $C_j(k+1)$ criterion.

The final weight values for the criteria were then calculated in the third step, which were determined by two conditions.

- The first condition involves calculating the ratio of the final weight values of the criteria based on the preferences of the compared criteria in the second step.
- The second condition requires the final weight value to satisfy certain transfer conditions.

Using a nonlinear single-objective programming model, we have (Equation (2)):

$$\text{Min } \chi \tag{2}$$

s.t.

$$\left|\frac{w_{j(k)}}{w_{j(k+1)}}-\varphi_{k/k+1}\right| \leq \chi, \forall \text{j}$$

$$\left|\frac{w_{j(k)}}{w_{j(k+2)}}-\varphi_{k/k+1} \otimes \varphi_{k+1/k+2}\right| \leq \chi, \forall \text{j}$$

$$\sum_{j=1}^{n} \omega_j = 1, \omega_j \geq 0, \forall \text{j}$$

In the subsequent phases of the risk management process, the risk assessment is crucial for determining the appropriate course of action. However, if real and reliable data are not available, the risk analysis of pipeline performance may lead to inaccuracies in predicting parameters and making decisions under uncertain conditions. Fuzzy theory is a valuable tool for modeling uncertainty and conducting risk assessments [2, 35]. In this study, a fuzzy inference system with two fuzzy inference subsystems was developed to fully consider both the assessment and response aspects. The rules of the fuzzy inference system were derived based on the literature and expert opinions. In the first step, the fuzzy inference system takes the sum of the probabilities of the critical factors for the possibility of corrosion and the consequences of pipeline corrosion as input and outputs the risk level. Using the probability of each criterion, the corrosion risk for the segment under investigation, and the result of the corrosion condition of this segment, the risk level for this segment was calculated. The assessment of corrosion has a significant impact on the determination of strategies to prevent it. In this study, the net strategy was determined based on a sensitivity-risk priority index chart. In the second phase, "risk level, coating condition, and cathodic protection system" were used as inputs and the type of corrective action was determined as output. The fuzzy inference system model was developed using MATLAB software. The numbers obtained for each segment of the pipelines indicate the corrosion risk status and the actions required in that segment. The flowchart in Figure 3 illustrates the steps involved in this study.

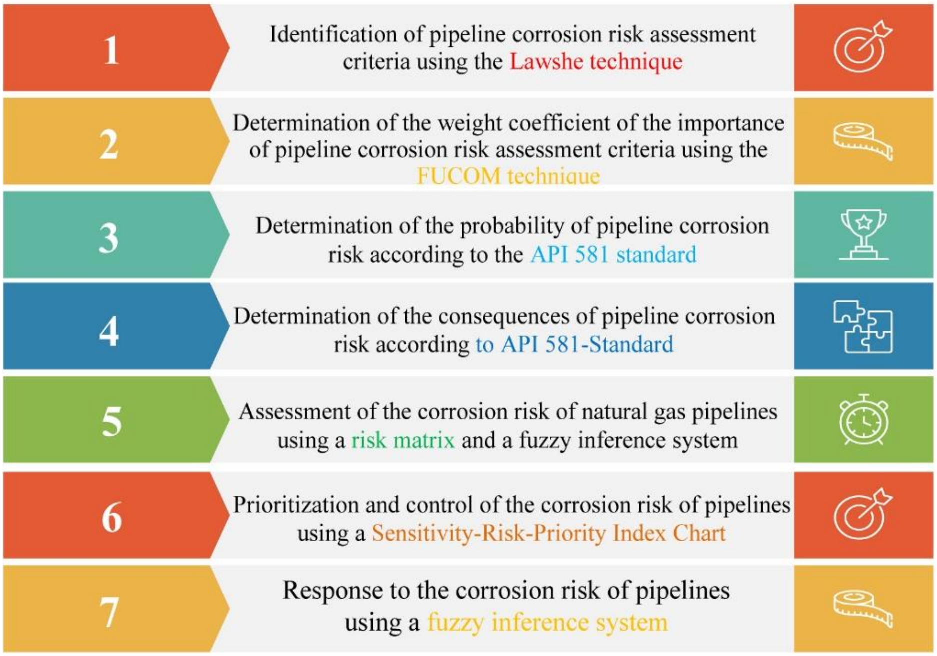


Figure 3. Flowchart of research implementation

4. Results

4.1. Identification of the criteria for corrosion risk assessment of pipelines

Pipeline networks are always at risk due to various factors, including corrosion. Effective decision-making requires the evaluation and determination of the functional value of the phenomena under study, which implies the identification of key indicators. The assessment of the critical factors of corrosion will have a significant impact on the determination of net strategies. Effective risk management requires the identification and ranking of critical risks to mitigate their consequences. The identified risks were used to develop a response plan to improve the corrosion situation. Although various studies have investigated the critical factors of corrosion, it is impossible to consider all factors in corrosion risk management, and some factors are commonly overlooked although they are important to facilitate the design of fuzzy inference systems and avoid complexity and multiplicity. Fuzzy laws require the identification of critical factors. The corrosion process has been described in different ways in different studies. The crucial factors identified in this study are presented in Table 1 based on expert opinions.

In general, the literature and expert opinions show that the criteria "long pipeline service life, in-line inspection [23], inspection frequency, soil resistivity, soil pH, soil moisture, redox reduction-oxidation potential [19], cathodic protection, pipeline coating, hydrogen sulfide gas, carbon dioxide gas, lack of injection of corrosion inhibitors [17,33,36], soil salt [19,33], ambient temperature [33] has special attention compared to other criteria identified as input for the fuzzy inference system. Since sweet natural gas has no potential for internal corrosion and appropriate measures are taken, the factors related to internal corrosion are removed from the identified factors. There is a huge number of elements in various studies which has been described as effective components in gas pipelines corrosion that critical factors, in accordance with elite's notion, were identified in according to Table 1.

Table 1. Critical factors of corrosion [1]

Factor symbol	Critical factor for corrosion of natural gas pipelines	Sour natural gas	Sweet natural gas
C_1	Service life of pipelines	●	●
C_2	Frequency of inspection	●	●
C_3	In-line inspection	●	●
C_4	Cathodic protection	●	●
C_5	Pipeline coating	●	●
C_6	Soil resistivity	●	●
C_7	Soil salt	●	●
C_8	Soil moisture	●	●
C_9	Redox reduction-oxidation potential	●	●
C_{10}	pH value of the soil	●	●
C_{11}	Operating temperature	●	●
C_{12}	Hydrogen sulfide gas	●	×
C_{13}	Carbon dioxide gas	●	×
C_{14}	Injection of a corrosion inhibitor	●	×

4.2. Analysis of the criteria for corrosion risk assessment of pipelines

Determining the threshold values for these indicators is a complex process that often requires the solution of optimization or laboratory problems. In this study, the thresholds for the risk assessment indicators were established through the research and laboratory results. Some assessment indicators such as "in-line inspection, inspection frequency, corrosion inhibitor injection, coating, cathodic protection, and acid gas separation" were established without prior on-site investigations to determine their thresholds. These limits were set by research experts. The qualitative forms of acid gasses, including CO_2 and H_2S, were determined under the general title of "acid gas". The assignment of factors in the fuzzy inference system model in this study is based on Table 2, which is presented below.

For all factors, for the verbal variable "very harsh" class 5, for the verbal phrase "harsh" class 4, for the verbal phrase "relatively harsh" class 3, for the verbal phrase "mild harsh" class 2 and for the verbal phrase "very mild" Class 1 is defined. The variables have a range of 5 or 3 degrees from 1 to 9 so the verbal variable "very harsh" has a numerical value of 9 and "very mild" has a numerical value of 1. The numerical values of these verbal expressions are listed in Table 3.

Table 2. Factors Affecting Corrosion

Verbal variable	**Soil resistivity (m^2)**	**Soil moisture (%)**	**Soil salt (%)**	**Redox potential (mV)**
Very harsh (VH)	<10	60-85	>0.75	<100
Harsh (H)	10-20	50-60	0.15-0.75	100-200
Relatively harsh (M)	20-50	25-50	0.05-0.15	200-400
Mild harsh (II)	50-100	1-25	<0.05	>400
Very mild harsh (I)	>100	-	-	-
	[13]	[30]	[19]	[30]

Verbal variable	**Inhibitor**	**Cathodic protection**	**Inspection frequency**	**Coating**
Very harsh (VH)	No inhibitor used	No effect	Unplanned	No/improper coating
Harsh (H)	No inhibitor used	Low effect	Rarely	No/improper coating
Relatively harsh (M)	No inhibitor used	Relatively low effect	Delayed	Coating needs to be replaced
Mild harsh (II)	Inhibitor used	Effective	Timely	Proper coating
Very mild harsh (I)	Inhibitor used	Proper effect	Proactive	Proper coating
	Expert opinions	Expert opinions	Expert opinions	Expert opinions

Verbal variable	**Acid gas**	**Pipeline inspection**	**Temperature**	**pH**	**Lifetime**
Very harsh (VH)	No separation	No known inspection procedure	High/very low	<4.5	30~50 Years
Harsh (H)	Incomplete separation	No inspection procedure	High/very low	4.5-5.5	30~50 Years
Relatively harsh (M)	Incomplete separation	Occasionally	Other	5.5-7	15~30 Years
Mild harsh (II)	Complete separation	Full inspection	Other	7-8.5	0~15 Years
Very mild harsh (I)	Complete separation	Intelligent inspection	Other	>8.5	-
	Expert opinions	[15]	Expert opinions	[19]	[14]

In addition, high and very low temperatures increase the corrosion rate, which is included in the fuzzy model according to Table 3.

Using fuzzy logic, the evaluation indicators were considered as inputs to the fuzzy control system for pairwise comparisons, and a corresponding fuzzy membership function was defined for each. A total of 78 pairwise comparisons between corrosion evaluation indices based on secretions were investigated, and owing to the limitations in presentation, only crucial observations have been described.

As for soil corrosion factors, important comparisons between soil parameters such as "soil resistivity, soil moisture, soil salinity, pH, and redox potential" are shown in Figures 4-8. It has been observed that pipelines exposed to harsh soils for longer than their lifetime show an increasing corrosion trend, as shown by Azoor et al. [6].

This emphasizes the importance of developing a reliable approach for estimating smart management of pipeline corrosion. In addition, the degree of soil corrosiveness is determined by the maximum correlation between the parameters "redox potential, soil resistivity, pH, moisture, and soil salinity" based on five levels, as shown in Table 2.

Table 3. Evaluation of factors based on verbal variables [8]

Verbal variable	Corresponding fuzzy numbers
VH	(8.5,10,10)
H	(6,7.5,9)
M	(3.5,5,6.5)
L	(1,2.5,4)
VL	(0,0,1.5)

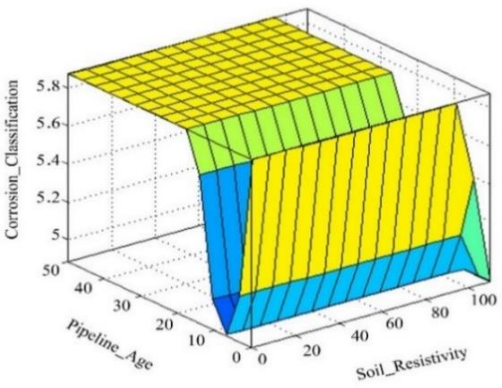


Figure 4. Corrosion risk based on soil resistivity and pipeline lifetime

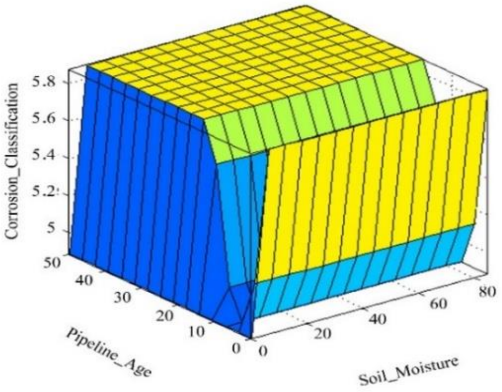
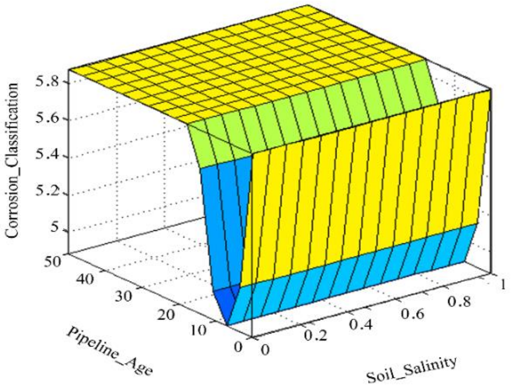


Figure 5. Corrosion risk based on soil moisture and pipeline lifetime



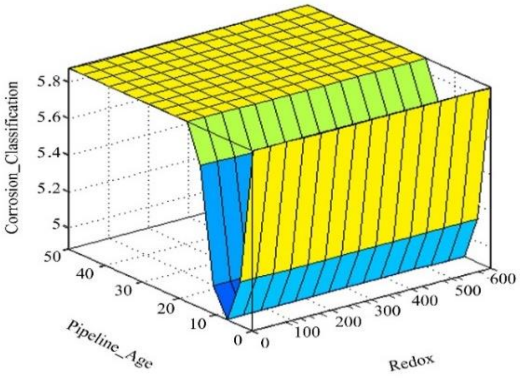
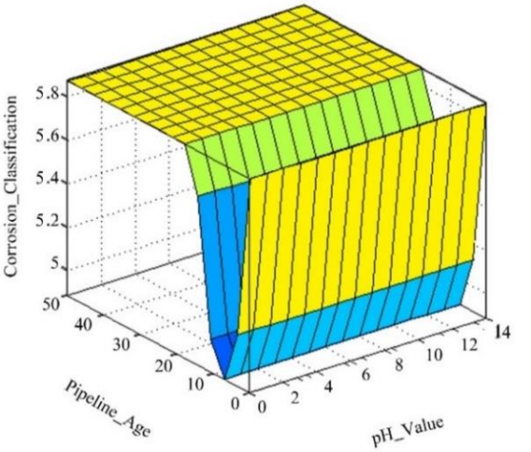


Figure 6. Corrosion risk based on soil salt and pipeline lifetime

Figure 7. Corrosion risk based on redox potential and pipeline lifetime



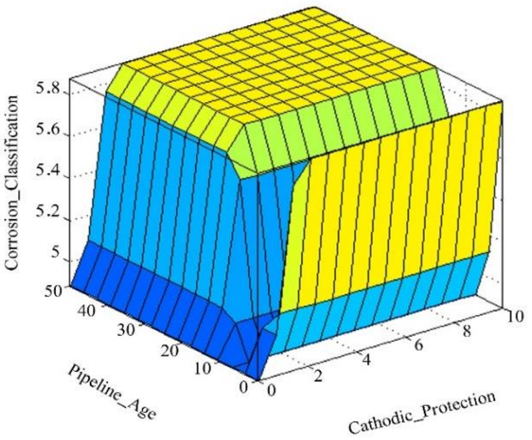
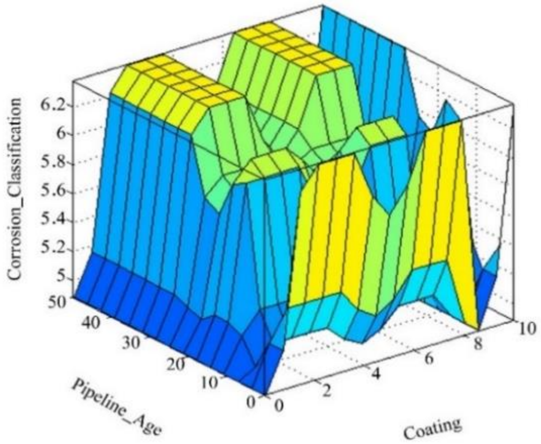


Figure 8. Corrosion risk based on soil pH and pipeline lifetime

Figure 9. Corrosion risk based on cathodic protection and pipeline lifetime

Cathodic disbondment is widely recognized as the main cause of coating damage on coated pipelines. Effective monitoring of cathodic protection can significantly reduce the occurrence of cathodic disbondment and maintain the long-term integrity of the pipeline, as shown in Figures 9-11 and supported by the research of [32].11 As shown in Figure 11, inspection plays a critical role in pipeline service life. Corrosion monitoring is a valuable strategy in the fight against corrosion and offers significant economic benefits to the gas industry.

The synergistic effect of corrosive acid gasses such as H_2S and CO_2 significantly increases the corrosion rate and often leads to the corrosion of pipelines. The use of inhibitors helps to prevent the expansion of the area of acid gas corrosion, as shown in Figure 12. However, corrosion inhibitors can be ineffective. To increase their effectiveness, it is recommended to propose deterrents that do not consider environmental aspects or use prohibited substances, which is consistent with the findings of Fink et al. [12] and Qin et al. [27].



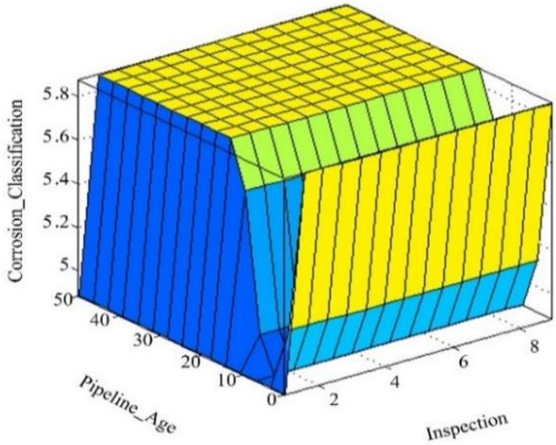


Figure 10. Corrosion risk based on cathodic protection and coating

Figure 11. Corrosion risk based on cathodic protection and inspection

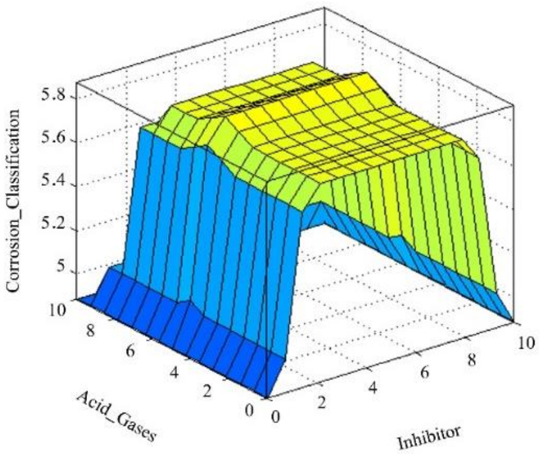


Figure 12. Corrosion risk based on acidic and inhibitory gasses

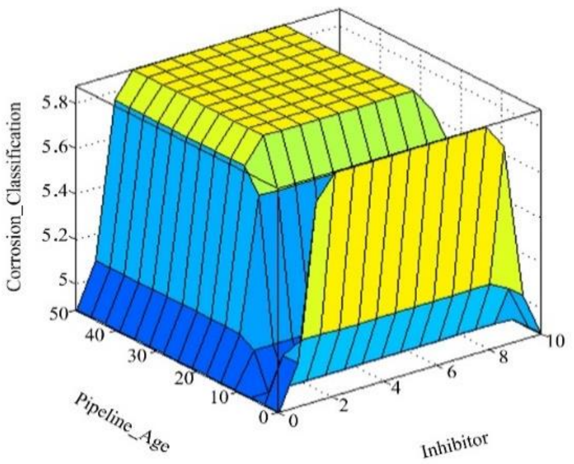


Figure 13. Corrosion risk based on inhibitors and pipeline lifetime

Based on the results shown in Figures 4-13, it is clear that the probability of corrosion can only be reduced if the soil corrosion factors, inhibitor, coating, and cathodic protection are optimal.

4.2.1. Determining the Importance and Weight of the criteria for corrosion risk assessment of pipelines

4.2.1.1. Sour natural gas

A key aspect of analysing the risk assessment factors is evaluating the weight coefficient of each factor. The ranking of the criteria based on expert opinion and their importance is shown in Table 4. A 9-point scale was used to prioritize the criteria and the experts' preferences were used to establish comparative priorities.

Table 4. Comparative prioritization of critical factors of natural gas pipeline Corrosion by experts

$C_1>$	$C_2=$	$C_3>$	$C_5=$	$C_4>$	$C_{14}>$	$C_{13}>$	$C_{12}>$	$C_9>$	$C_6=$	$C_8>$	$C_{11}>$	$C_7>$	C_{10}
9	8	8	7	7	6	6	5	5	4	4	3	2	1

Following the prioritization of the criteria by the experts, weight coefficients w_k were calculated based on the comparative priorities.

$$\frac{w_{c1}}{w_{c2}}=\frac{9}{8}=1.125 \quad \frac{w_{c2}}{w_{c3}}=\frac{8}{8}=1 \quad \frac{w_{c3}}{w_{c5}}=\frac{8}{7}=1.143 \quad \frac{w_{c5}}{w_{c4}}=\frac{7}{7}=1 \quad \frac{w_{c4}}{w_{c14}}=\frac{7}{6}=1.167$$

$$\frac{w_{c14}}{w_{c13}}=\frac{6}{6}=1 \quad \frac{w_{c13}}{w_{c12}}=\frac{6}{5}=1.2 \quad \frac{w_{c12}}{w_{c9}}=\frac{5}{5}=1 \quad \frac{w_{c9}}{w_{c6}}=\frac{5}{4}=1.25 \quad \frac{w_{c6}}{w_{c8}}=\frac{4}{4}=1$$

$$\frac{w_{c8}}{w_{c11}}=\frac{4}{3}=1.33 \quad \frac{w_{c11}}{w_{c7}}=\frac{3}{2}=1.5 \quad \frac{w_{c7}}{w_{c10}}=\frac{2}{1}=2$$

Other weight coefficients were calculated using the mathematical transferability condition and the expert opinions as described below.

$$\frac{w_{c1}}{w_{c3}}=\frac{w_{c1}}{w_{c2}}\times\frac{w_{c2}}{w_{c3}}=1.25\times1=1.25 \quad \frac{w_{c2}}{w_{c5}}=\frac{w_{c2}}{w_{c3}}\times\frac{w_{c3}}{w_{c5}}=1\times1.143=1.143 \quad \frac{w_{c3}}{w_{c4}}=\frac{w_{c3}}{w_{c5}}\times\frac{w_{c5}}{w_{c4}}=1.143\times1=1.143$$

$$\frac{w_{c5}}{w_{c14}}=\frac{w_{c5}}{w_{c4}}\times\frac{w_{c4}}{w_{c14}}=1\times1.167=1.167 \quad \frac{w_{c4}}{w_{c13}}=\frac{w_{c4}}{w_{c14}}\times\frac{w_{c14}}{w_{c13}}=1.167\times1=1.167 \quad \frac{w_{c14}}{w_{c12}}=\frac{w_{c14}}{w_{c13}}\times\frac{w_{c13}}{w_{c12}}=1\times1.2=1.2$$

$$\frac{w_{c13}}{w_{c9}}=\frac{w_{c13}}{w_{c12}}\times\frac{w_{c12}}{w_{c9}}=1.2\times1=1.2 \quad \frac{w_{c12}}{w_{c6}}=\frac{w_{c12}}{w_{c9}}\times\frac{w_{c9}}{w_{c6}}=1\times1.25=1.25 \quad \frac{w_{c9}}{w_{c8}}=\frac{w_{c9}}{w_{c6}}\times\frac{w_{c6}}{w_{c8}}=1.25\times1=1.25$$

$$\frac{w_{c6}}{w_{c11}}=\frac{w_{c6}}{w_{c8}}\times\frac{w_{c8}}{w_{c11}}=1\times1.33=1.33 \quad \frac{w_{c8}}{w_{c7}}=\frac{w_{c8}}{w_{c11}}\times\frac{w_{c11}}{w_{c7}}=1.33\times1.5=1.995 \quad \frac{w_{c11}}{w_{c10}}=\frac{w_{c11}}{w_{7}}\times\frac{w_{c7}}{w_{c10}}=1.5\times2=3$$

To determine the weight of the criteria, a mathematical model was formulated based on comparisons as Equation (3).

The results of solving the mathematical model using Lingo software are shown in Table 5. The weights of the criteria are shown in Figure 14.

$$\text{Min } \chi \tag{3}$$

s.t.

$$\left|\frac{w_{c1}}{w_{c2}} - 1.125\right| \leq \chi\,,\ \left|\frac{w_{c2}}{w_{c3}} - 1\right| \leq \chi,\ \left|\frac{w_{c3}}{w_{c5}} - 1.143\right| \leq \chi\,,\ \left|\frac{w_{c5}}{w_{c4}} - 1\right| \leq \chi,\ \left|\frac{w_{c4}}{w_{c14}} - 1.167\right| \leq \chi,\ \left|\frac{w_{c14}}{w_{c13}} - 1\right| \leq \chi,$$
$$\left|\frac{w_{c13}}{w_{c12}} - 1.2\right| \leq \chi,\ \left|\frac{w_{c12}}{w_{c9}} - 1\right| \leq \chi,\ \left|\frac{w_{c9}}{w_{c6}} - 1.25\right| \leq \chi\,,\ \left|\frac{w_{c6}}{w_{c8}} - 1\right| \leq \chi,\ \left|\frac{w_{c8}}{w_{c11}} - 1.33\right| \leq \chi,\ \left|\frac{w_{c11}}{w_{c7}} - 1.5\right| \leq \chi,$$
$$\left|\frac{w_{c7}}{w_{c10}} - 2\right| \leq \chi\,,\ \left|\frac{w_{c1}}{w_{c3}} - 1.25\right| \leq \chi,\ \left|\frac{w_{c2}}{w_{c5}} - 1.143\right| \leq \chi,\ \left|\frac{w_{c3}}{w_{c4}} - 1.143\right| \leq \chi\,,\ \left|\frac{w_{c5}}{w_{c14}} - 1.167\right| \leq \chi,\ \left|\frac{w_{c4}}{w_{c13}} - 1.167\right| \leq,$$
$$\left|\frac{w_{c14}}{w_{c12}} - 1.2\right| \leq \chi,\ \left|\frac{w_{c13}}{w_{c9}} - 1.2\right| \leq \chi\,,\ \left|\frac{w_{c12}}{w_{c6}} - 1.25\right| \leq \chi,\ \left|\frac{w_{c9}}{w_{c8}} - 1.25\right| \leq \chi\,,\ \left|\frac{w_{c6}}{w_{c11}} - 1.33\right| \leq \chi,\ \left|\frac{w_{c8}}{w_{c7}} - 1.995\right| \leq \chi,$$
$$\left|\frac{w_{c11}}{w_{c10}} - 3\right| \leq \chi$$

$$\sum_1^{14} \omega_j = 1, \omega_j \geq 0, \forall \text{j}$$

Table 5. Weight of the natural gas pipelines corrosion assessment factors

ω_{C14}	ω_{C13}	ω_{C12}	ω_{C11}	ω_{C10}	ω_{C9}	ω_{C8}	ω_{C7}	ω_{C6}	ω_{C5}	ω_{C4}	ω_{C3}	ω_{C2}	ω_{C1}
0.07958	0.07748	0.0642	0.0363	0.0121	0.0625	0.0497	0.0247	0.0497	0.096	0.0923	0.1092	0.1135	0.1321

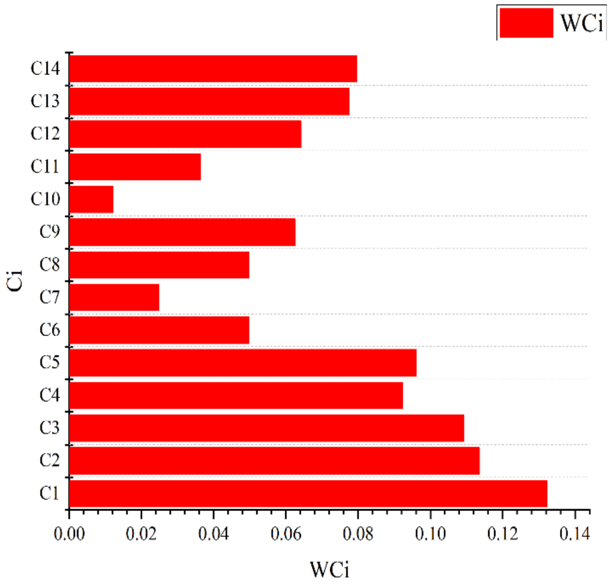


Figure 14. Ranking of the natural gas pipelines corrosion assessment factors weight

4.2.1.2. Sweet natural gas

Based on the experts' priorities for the criteria, the weight coefficients w_k were calculated according to the comparative priorities.

$$\frac{w_{c1}}{w_{c2}} = \frac{9}{8} = 1.125 \quad \frac{w_{c2}}{w_{c3}} = \frac{8}{8} = 1 \quad \frac{w_{c3}}{w_{c5}} = \frac{8}{7} = 1.143 \quad \frac{w_{c5}}{w_{c4}} = \frac{7}{7} = 1 \quad \frac{w_{c4}}{w_{c9}} = \frac{7}{5} = 1.4$$
$$\frac{w_{c9}}{w_{c6}} = \frac{5}{4} = 1.25 \quad \frac{w_{c6}}{w_{c8}} = \frac{4}{4} = 1 \quad \frac{w_{c8}}{w_{c11}} = \frac{4}{3} = 1.33 \quad \frac{w_{c11}}{w_{c7}} = \frac{3}{2} = 1.5 \quad \frac{w_{c7}}{w_{c10}} = \frac{2}{1} = 2$$

Additional weight coefficients were determined using the mathematical transferability condition and the expert opinions, as described below.

$$\frac{w_{c1}}{w_{c3}} = \frac{w_{c1}}{w_{c2}} \times \frac{w_{c2}}{w_{c3}} = 1.25 \times 1 = 1.25 \quad \frac{w_{c2}}{w_{c5}} = \frac{w_{c2}}{w_{c3}} \times \frac{w_{c3}}{w_{c5}} = 1 \times 1.143 = 1.143 \quad \frac{w_{c3}}{w_{c4}} = \frac{w_{c3}}{w_{c5}} \times \frac{w_{c5}}{w_{c4}} = 1.143 \times 1 = 1.143$$
$$\frac{w_{c5}}{w_{c9}} = \frac{w_{c5}}{w_{c4}} \times \frac{w_{c4}}{w_{c9}} = 1 \times 1.4 = 1.4 \quad \frac{w_{c4}}{w_{c6}} = \frac{w_{c4}}{w_{c9}} \times \frac{w_{c9}}{w_{c6}} = 1.4 \times 1.25 = 1.75 \quad \frac{w_{c9}}{w_{c8}} = \frac{w_{c9}}{w_{c6}} \times \frac{w_{c6}}{w_{c8}} = 1.25 \times 1 = 1.25$$
$$\frac{w_{c6}}{w_{c11}} = \frac{w_{c6}}{w_{c8}} \times \frac{w_{c8}}{w_{c11}} = 1 \times 1.33 = 1.33 \quad \frac{w_{c8}}{w_{c7}} = \frac{w_{c8}}{w_{c11}} \times \frac{w_{c11}}{w_{c7}} = 1.33 \times 1.5 = 1.995 \quad \frac{w_{c11}}{w_{c10}} = \frac{w_{c11}}{w_{c7}} \times \frac{w_{c7}}{w_{c10}} = 1.5 \times 2 = 3$$

To determine the weight of the criteria, a mathematical model based on comparisons was formulated as Equation (4).

$$
\begin{aligned}
&\text{Min } \chi \qquad (4)\\
&\text{s.t.}\\
&\left|\frac{w_{c1}}{w_{c2}}-1.125\right|\le\chi,\ \left|\frac{w_{c2}}{w_{c3}}-1\right|\le\chi,\ \left|\frac{w_{c3}}{w_{c5}}-1.143\right|\le\chi,\ \left|\frac{w_{c5}}{w_{c4}}-1\right|\le\chi,\ \left|\frac{w_{c4}}{w_{c9}}-1.4\right|\le\chi,\ \left|\frac{w_{c9}}{w_{c6}}-1.25\right|\le\chi,\\
&\left|\frac{w_{c6}}{w_{c8}}-1\right|\le\chi,\ \left|\frac{w_{c8}}{w_{c11}}-1.33\right|\le\chi,\ \left|\frac{w_{c11}}{w_{c7}}-1.5\right|\le\chi,\ \left|\frac{w_{c7}}{w_{c10}}-2\right|\le\chi,\\
&\left|\frac{w_{c1}}{w_{c3}}-1.25\right|\le\chi,\ \left|\frac{w_{c2}}{w_{c5}}-1.143\right|\le\chi,\ \left|\frac{w_{c3}}{w_{c4}}-1.143\right|\le\chi,\ \left|\frac{w_{c5}}{w_{c9}}-1.4\right|\le\chi,\ \left|\frac{w_{c4}}{w_{c6}}-1.75\right|\le\chi,\ \left|\frac{w_{c9}}{w_{c8}}-1.25\right|\le,\\
&\left|\frac{w_{c6}}{w_{c11}}-1.33\right|\le\chi,\ \left|\frac{w_{c8}}{w_{c7}}-1.995\right|\le\chi,\ \left|\frac{w_{c11}}{w_{c10}}-3\right|\le\chi\\
&\textstyle\sum_1^{14}\omega_j=1,\ \omega_j\ge 0,\ \forall j
\end{aligned}
$$

The results of solving the mathematical model with the Lingo software are listed in Table 6. Figure 15 shows the ranking of the importance of the criteria in terms of their weight.

Table 6. Weight of the sweet natural gas pipelines corrosion assessment factors

ω_{C11}	ω_{C10}	ω_{C9}	ω_{C8}	ω_{C7}	ω_{C6}	ω_{C5}	ω_{C4}	ω_{C3}	ω_{C2}	ω_{C1}
0.05183	0.01727	0.08617	0.0689	0.0345	0.0689	0.1206	0.12065	0.1379	0.13790	0.1551

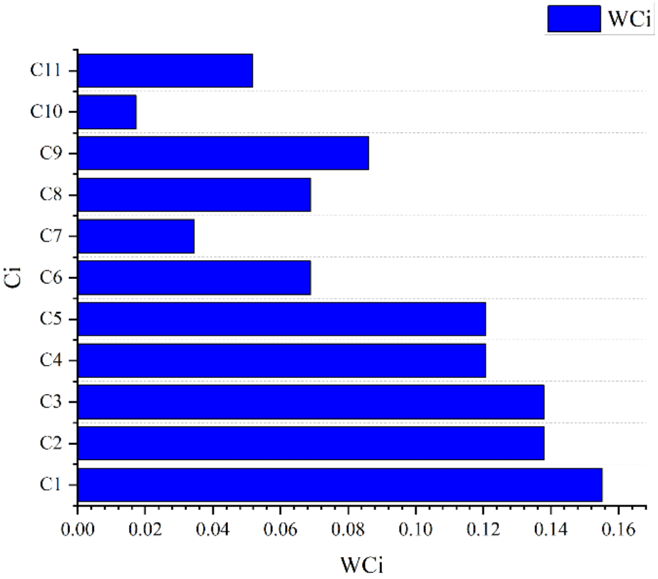


Figure 15. Ranking of the sweet natural gas pipelines corrosion assessment factors weight

- The results show that factors such as pipeline life, inspection frequency, in-line inspection, coating, and cathodic protection are most crucial in both sour and sweet gases. Among these critical factors, pH is the least important.
- In sweet gas, factors such as inspection frequency and inline inspection as well as protective measures such as cathodic protection and pipeline coating are equally important.
- After pipeline coating, inhibitor injection, and acid gases are more critical than other key factors for sour gas.

The FUCOM technique is advantageous because it reduces the number of pairwise comparisons and minimizes the number of calculations. It is recommended to create optimal conditions for factors such as inspection frequency, in-line inspection, coating, cathodic protection, and inhibitor injection to extend the service life of pipelines.

4.2.2. Assessing the probability of occurrence of pipeline corrosion risk

The probability of occurrence refers to the identification of potential failures before they occur due to one or more degradation mechanisms under specific operating conditions. Since the occurrence of corrosion is equivalent to subsets of the critical factor space, the community of occurrence of critical factors is actually the

community of their corresponding subsets. The calculated corrosion event probability was derived from the sum of the incompatible event probabilities according to Equation (5).
The weight assigned to each critical factor, determined by Equation (10), was classified according to Table 7.

$$\begin{aligned} &P_{Corrosion}=P_{C1}+P_{C2}+P_{C3}+P_{C4}+P_{C5}+P_{C6}+P_{C7}+P_{C8}+P_{C9}+P_{C10}+P_{C11}+P_{C12}+P_{C13}+P_{C14} && \{\text{natural gas}\} \\ &P_{Corrosion}=P_{C1}+P_{C2}+P_{C3}+P_{C4}+P_{C5}+P_{C6}+P_{C7}+P_{C8}+P_{C9}+P_{C10}+P_{C11} && \{\text{sweet natural gas}\} \end{aligned} \qquad (5)$$

Table 7. Classification of POF factors [5]

Class	Annual probability of failure, occurrence/year	Degradation factor
1	$Pf(t,I_E)\leq 3.06E\text{-}05$	$D_{f\text{-}total}\leq 1$
2	$3.06E\text{-}05< Pf(t,I_E)\leq 3.06E\text{-}04$	$1<D_{f\text{-}total}\leq 10$
3	$3.06E\text{-}04< Pf(t,I_E)\leq 3.06E\text{-}03$	$10<D_{f\text{-}total}\leq 100$
4	$3.06E\text{-}03< Pf(t,I_E)\leq 3.06E\text{-}02$	$100<D_{f\text{-}total}\leq 1000$
5	$Pf(t,I_E)>3.06E\text{-}02$	$D_{f\text{-}total}>1000$

If essential statistical data on critical factors are not available, the probability of corrosion risk is determined using Table 7 and in compliance with the API 581 standard [5].

4.2.3. Determining the consequences of pipelinecorrosion risk

Pipeline accidents can lead to significant human, financial, and environmental damage. Although the probability of failure may be low in many areas, the consequences of failure can be catastrophic. It is therefore crucial to assess both the possibility and the consequences of an accident. The consequences of a pipeline failure depend on the fluid in the pipeline and the environmental conditions. These two factors can interact in complex and variable ways. The leakage rate of the fluid and the environmental conditions are variables that can influence the consequence and are often unpredictable. The consequence of a failure is the result of a failure event in relation to the environmental conditions. The loss of the ability to contain hazardous liquids (leakage) can cause damage to surrounding equipment, harm personnel, and have a negative impact on the environment. This consequence can be attributed to safety, environmental, and economic factors. The consequence of failure (COF) classification is shown in Table 8.

Table 8 Classification of COF factors in environmental dimensions [5]

Class	Degradation results in (ft^2)
A	$CA_f^{flam}\leq 100$
B	$100<CA_f^{flam}\leq 1{,}000$
C	$1{,}000< CA_f^{flam}\leq 10{,}000$
D	$10{,}000< CA_f^{flam}\leq 100{,}000$
E	$CA_f^{flam}>100{,}000$

4.2.4. Natural gas pipelines risk assessment

Corrosion risk assessment is the process of estimating the probability of a corrosion event and its impact on society, the environment, and the economy, which includes three components: "Risk identification, analysis, and prioritization" The failure mechanisms were examined according to "Exposure, mitigation effects and resistance to corrosion risks" Exposure is used to express the severity of the threat to pipelines without corrosion protection methods. Processes such as the application of a coating and a cathodic protection system as well as all measures that lead to a reduction of injuries are categorized as reduction processes. Resilience refers to the ability of a pipeline to withstand failures. For time-dependent mechanisms such as corrosion, the resistance depends on the wall thickness [24]. Since there is no information on the wall thickness or it cannot be updated, a risk assessment based on indicators was carried out. The risk assessment based on indicators and numerical points is assigned to critical indicators that have an impact on the safety of the pipeline. The risk assessment was carried out in accordance with the API 581 standard [5] using the risk matrix shown in Figure 16. The probability of occurrence refers to the detection of potential failures before they occur due to one or more degradation mechanisms under specific operating conditions. The assessment of the risk of failure is determined as a function of time as it increases due to thickness reduction, cracking, or other failure mechanisms. However, the consequences of risk remain constant over time. The risk levels of pipelines can be observed using a risk matrix, which is an effective means of representing the risk distribution of different components in a processing unit without using numerical values. The purpose of using a risk matrix is to identify the critical areas that require more attention during the inspection. Risk management decisions in cells of the same color also depend on the predominant risk component.

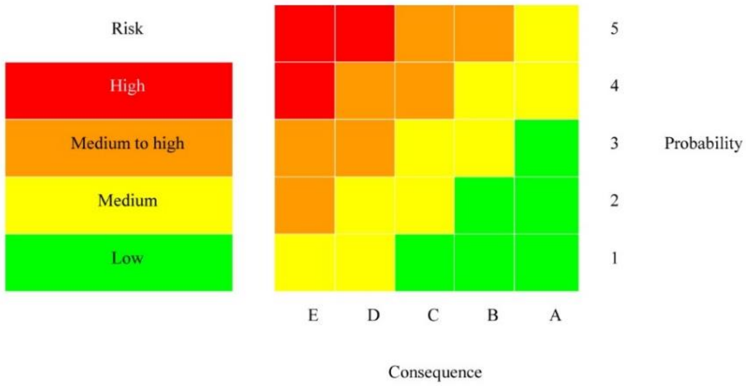


Figure 16. Risk matrix [24]

The risk matrix illustrates the risk levels of pipelines and serves as an efficient method to visualize the risk distribution of different components in a processing unit without relying on numerical values. The aim is to identify the critical areas that require more attention during the inspection. Risk management decisions in cells of the same color depend on the dominant risk component. The proposed risk matrix comprises four levels: green and red cells, which represent acceptable risks, and orange and yellow cells, which represent high and medium risks respectively. The first phase inference system includes the assessment of two pipeline network failure scenarios and their impact on the environment, based on the API 581 standard [5].

4.2.4.1. Design of a fuzzy inference system for the assessment of pipeline corrosion risk

To design a fuzzy inference system for pipeline corrosion risk assessment, fuzzy logic is used to treat the assessment indicators as input to the fuzzy control system. Each indicator is assigned a corresponding fuzzy membership function. To create the fuzzy inference system, fuzzy logic rules are established that describe the relationships between the fuzzy sets and their effects on the performance of the corrosion risk management system. The rules are executed to the extent that they match the input. The model relies on the knowledge and experience of academic and industrial experts for fuzzy inference. The proposed model includes two input variables, one output variable, and 25 conditional if-then rules. The indicators were evaluated with triangular fuzzy membership functions based on the verbal variables. The architecture of the fuzzy inference system for risk assessment is shown in Figure 17.

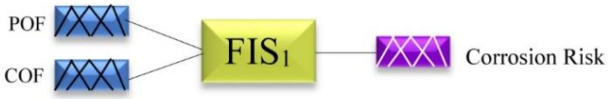
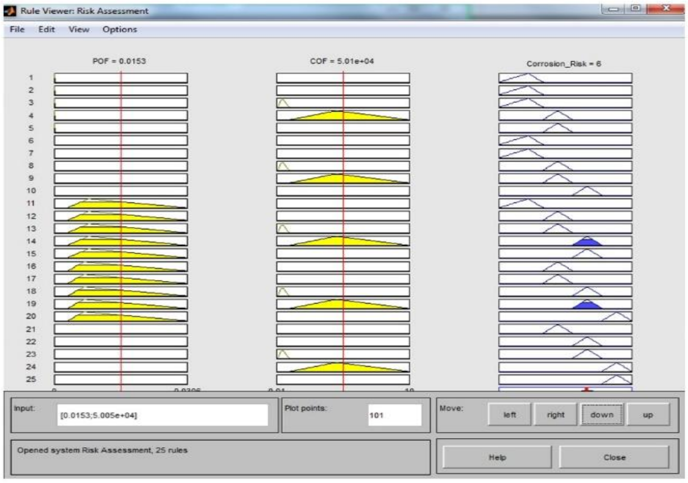


Figure 17. Architecture of the fuzzy inference system for risk assessment

This paper presents a two-stage fuzzy inference system that thoroughly considers different aspects of risk assessment and response to pipeline corrosion risk. The proposed fuzzy inference system consists of two fuzzy inference systems. In the first fuzzy inference system, the corrosion risk of the pipelines was assessed on the basis of probability and consequence indicators. The second fuzzy inference system was developed to determine the maintenance and repair strategies based on the assessed risk level. The evaluation mechanism for the consequence of degradation according to the API 581 standard [5] was investigated with regard to the environmental dimensions. To qualitatively assess the risk of pipelines, a risk matrix was used as a screening tool for prioritization during inspection. The fuzzy inference system for risk assessment comprised 25 fuzzy rules for the environmental dimensions, as follows.

FIS1 Rules:
If (POF is 1) and (COF is A) then (Corrosin_Risk is 1)
If (POF is 1) and (COF is B) then (Corrosin_Risk is 1)
If (POF is 1) and (COF is C) then (Corrosin_Risk is 1)
If (POF is 1) and (COF is D) then (Corrosin_Risk is 2)
If (POF is 1) and (COF is E) then (Corrosin_Risk is 2)
If (POF is 2) and (COF is A) then (Corrosin_Risk is 1)
If (POF is 2) and (COF is B) then (Corrosin_Risk is 1)
If (POF is 2) and (COF is C) then (Corrosin_Risk is 2)
If (POF is 2) and (COF is D) then (Corrosin_Risk is 2)
If (POF is 2) and (COF is E) then (Corrosin_Risk is 3)
If (POF is 3) and (COF is A) then (Corrosin_Risk is 1)
If (POF is 3) and (COF is B) then (Corrosin_Risk is 2)
If (POF is 3) and (COF is C) then (Corrosin_Risk is 2)
If (POF is 3) and (COF is D) then (Corrosin_Risk is 3)
If (POF is 3) and (COF is E) then (Corrosin_Risk is 3)
If (POF is 4) and (COF is A) then (Corrosin_Risk is 2)
If (POF is 4) and (COF is B) then (Corrosin_Risk is 2)
If (POF is 4) and (COF is C) then (Corrosin_Risk is 3)
If (POF is 4) and (COF is D) then (Corrosin_Risk is 3)
If (POF is 4) and (COF is E) then (Corrosin_Risk is 4)
If (POF is 5) and (COF is A) then (Corrosin_Risk is 2)
If (POF is 5) and (COF is B) then (Corrosin_Risk is 3)
If (POF is 5) and (COF is C) then (Corrosin_Risk is 3)
If (POF is 5) and (COF is D) then (Corrosin_Risk is 4)
If (POF is 5) and (COF is E) then (Corrosin_Risk is 4)

Figure 18 shows the conditional rules defined in MATLAB software.



Input: [0.0153;5.005e+04]

Plot points: 101

Opened system Risk Assessment, 25 rules

Figure 18. Final rules of fuzzy inference system for corrosion risk assessment

Each row in this figure represents a fuzzy rule, and each column corresponds to an factor. The output shown in the last column was automatically calculated using the gravity method. The remaining columns show the membership functions of the inputs.

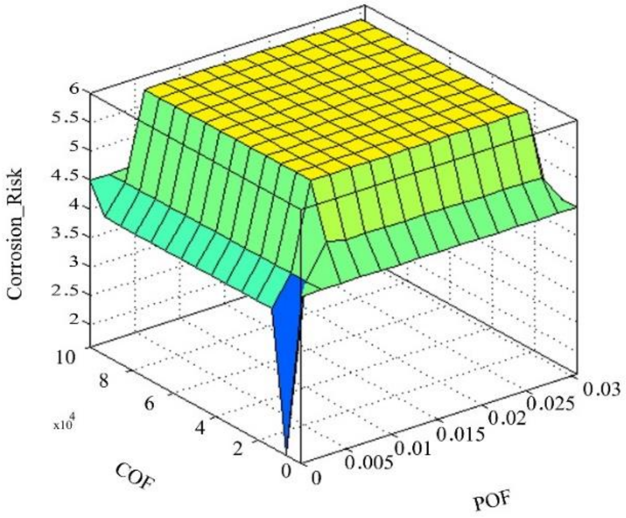


Figure 19. Output in relation to the COF and POF

Figure 19 shows that when implementing optimal arrangements in the gas industry, the highest risk arises at a relatively harsh and harsh level. In addition, the figure illustrates the importance of the consequence compared to the probability of occurrence.

4.3. Prioritization and control of corrosion risk in pipeline

A key aspect of risk management is making decisions about how to respond to a risk. To determine the appropriate maintenance and repair strategy for pipelines, a sensitivity-risk-priority index chart is used, with a horizontal axis representing the risk-priority index chart and a vertical axis representing the pipeline's sensitivity index.

The sensitivity depends on the pipeline lifetime indicators as shown in Table 9. Risk prioritization is based on the classification of the sensitivity-risk priority index chart.

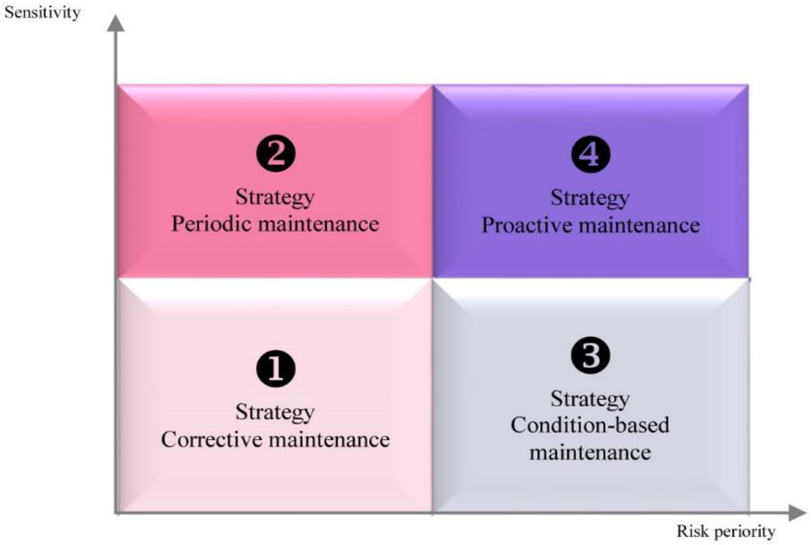


Figure 20. Determination of overall strategy based on overall risk prioritization index [15]

Table 9. Pipeline service life sensitivity [15]

Class	Sensitivity	Description
1	0-15٪	Low operational life
2	15-70٪	Service life
3	70-100٪	Wear-out life

The appropriate approach for maintenance and repair in this study is shown in Figure 20.

- Corrective maintenance: In the first quarter, there is a very low priority as the sensitivity index and risk priority are below the threshold. In this scenario, a net strategy is applied after a pipeline failure.
- Periodic maintenance: In the second quarter, the sensitivity was higher than the threshold value, but the risk priority was below the threshold value. This tactic is applied at regular intervals to reduce failures.
- Condition-based maintenance: In the third quarter, the priority is higher than the threshold for risk and lower for sensitivity. In this approach, the condition of the pipelines is of great importance and the net strategy is based on the data obtained from a set of system sensors and indicators. The real-time information is used to repair the pipelines.
- Proactive maintenance: In the fourth quarter, the priorities for risk and sensitivity were above the threshold value. In this quadrant, pipelines are considered high priority and critical. In this tactic, the cause of failure is identified and measures, such as redesign and reinstallation are taken to eliminate or adjust them.

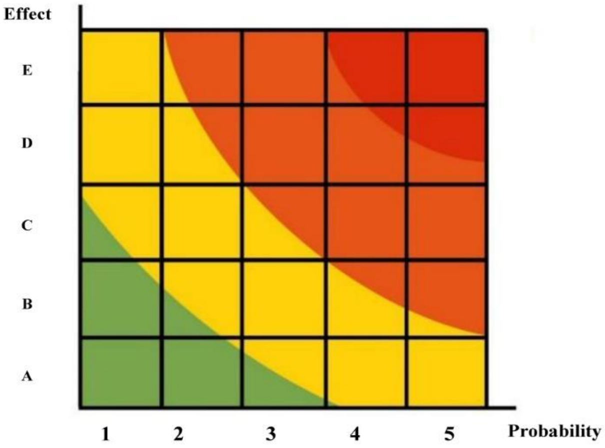


Figure 21. Risk matrix diagram [18]

4.4. Response to the risk of pipeline corrosion

The risk matrix is used to classify risks according to their severity in order to identify high-risk risks and develop corrective measures. By determining the priority of risks, a risk response plan can be created to improve opportunities and reduce threats in relation to objectives. The response to risk depends on the priority of the risk and the availability of resources.

The impact probability matrix categorization determines the response priority with fuzzy rules of the fuzzy inference system for pipeline maintenance and repair based on fuzzy rules and two inputs of corrosion risk and sensitivity. The fuzzy rules and the risk response system of the model are defined and designed in accordance with expert opinions. The model has two input variables and one output variable of the net operation, according to the architecture in Figure 22. The evaluation of each of the mentioned indicators is based on verbal variables with triangular fuzzy membership functions.

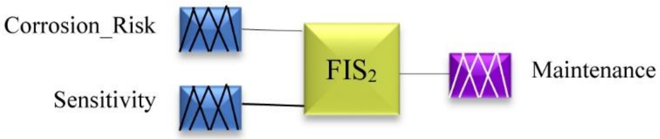


Figure 22. The architecture of the fuzzy inference system for response to risk

FIS$_2$ Rules:
If (Corrosion_Risk is 1) and (Sensitivity is 1) then (Maintenance is Corrective Maintenance)
If (Corrosion_Risk is 1) and (Sensitivity is 2) then (Maintenance is Corrective Maintenance)
If (Corrosion_Risk is 1) and (Sensitivity is 3) then (Maintenance is Scheduled_Maintenance)
If (Corrosion_Risk is 2) and (Sensitivity is 1) then (Maintenance is Corrective Maintenance)
If (Corrosion_Risk is 2) and (Sensitivity is 2) then (Maintenance is Corrective Maintenance)
If (Corrosion_Risk is 2) and (Sensitivity is 3) then (Maintenance is Scheduled_Maintenance)
If (Corrosion_Risk is 3) and (Sensitivity is 1) then (Maintenance is Condition_Based_Maintenance)
If (Corrosion_Risk is 3) and (Sensitivity is 2) then (Maintenance is Condition_Based_Maintenance)
If (Corrosion_Risk is 3) and (Sensitivity is 3) then (Maintenance is Proactive_Maintenance)
If (Corrosion_Risk is 4) and (Sensitivity is 1) then ((Maintenance is Condition_Based_Maintenance)
If (Corrosion_Risk is 4) and (Sensitivity is 2) then (Maintenance is Condition_Based_Maintenance)
If (Corrosion_Risk is 4) and (Sensitivity is 3) then (Maintenance is Proactive_Maintenance)

Figure 23 shows the output behavior of the designed risk-response system in response to changes in the input variables.

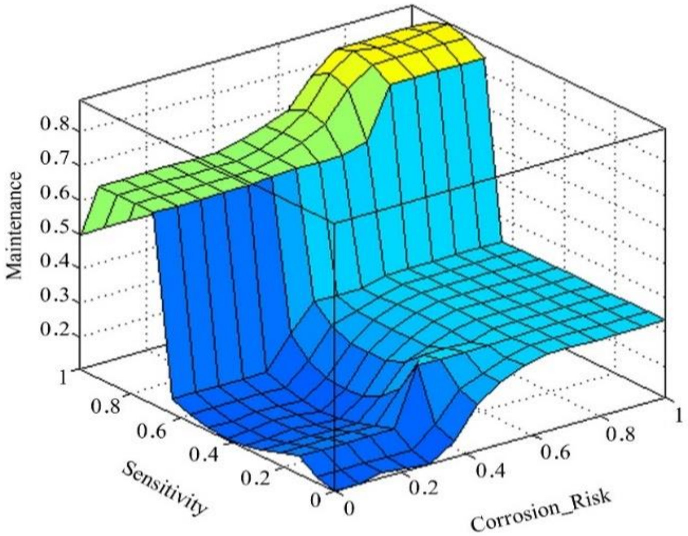


Figure 23. Variations of the risk level and sensitivity variables

The figure shows that the highest output of the maintenance and repair system occurs during the wear phase of the pipelines or when the risk level is low.

Managing and controlling the corrosion process is an important process for making informed decisions. Risk-based monitoring involves regular reporting of relevant information to support proactive management of operational risk. In this phase of the risk management process, the status of risks is assessed on the basis of the measures taken.

4.5.Sensitivity analysis in rating of risk assessment criteria of corrosion of pipelines

In the sensitivity analysis, a criterion was deleted each time and the sensitivity of rating to the removal of that criterion has been measured. A critical factor, which has the least sensitivity or the least changes in the output, is chosen as the best criterion. The yields of sensitivity analysis have been presented for sweet and sour natural gas pipelines in Table 10 and Figure 24 separately.

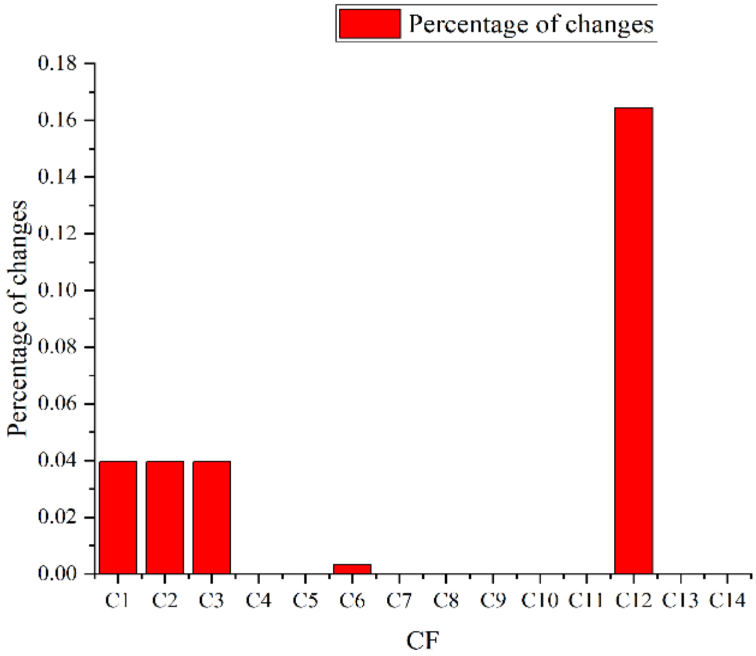


Figure 24 . Percentage of total changes in rating sour natural gas pipelines criteria

Table 10. The percent of yielded changes of removing each critical factor in rating risk assessment criteria of corrosion of sour natural gas pipelines

Symbol of factor	Critical factor of corrosion of natural gas pipelines	Percentage of total changes	Sensitivity rating
C_1	Longevity of pipelines	3.950066%	2
C_2	Inspection frequency	3.949089%	4
C_3	In-line inspection	3.949915%	3
C_4	Cathodic protection	0.000014%	6
C_5	Pipeline insulation	0.000003%	10
C_6	Specific resistance of soil	0.333672%	5
C_7	Salt of soil	0.000003%	10
C_8	Moisture of soil	0.000014%	6
C_9	Oxidation reduction potential | redox	0.000005%	9
C_{10}	PH of soil	0.000011%	7
C_{11}	Operating temperature	0.000006%	8
C_{12}	Hydrogen sulfide	16.449204%	1
C_{13}	Carbon dioxide	0.000006%	8
C_{14}	Corrosion inhibitor injection	0.000002%	11

In according to Table 11 and Figure 25, it is plain that in sour natural gas pipelines, the critical factor "Hydrogen sulfide gas" is considered as the first and the most sensitive element among other factors and the factor "Corrosion inhibitor injection" is the last with the least sensitive.

In according to Table 11 and Figure 25, it is plain that in sweet natural gas pipelines, the critical factor "Longevity of pipelines, Inspection frequency and In-line inspection are determined as the most sensitive factors.

The utilization of assessment and corrosion control approaches, has diminished or solved the issue of corrosion in a certain duration and for an operation unit. For reaching a stable and certain state in a set, it is demanded to collect information from the system and risk management repeatedly [29]. Despite of the studies, which have conducted in the field of risk assessment and corrosion risk prediction; however, it seems the study, which covers simultaneously all dimension of corrosion risk management, has never been fulfilled; furthermore, other researchers have done the prediction of corrosion complication, but they have never provided the preventive note, based on the forecast.

Table 11. The percent of yielded changes of removing each critical factor in rating risk assessment criteria of corrosion of sweet natural gas pipelines

Symbol of factor	Critical factor of corrosion of natural gas pipelines	Percentage of total changes	Sensitivity rating
C_1	Longevity of pipelines	12.500000%	1
C_2	Inspection frequency	12.500000%	1
C_3	In-line inspection	12.500000%	1
C_4	Cathodic protection	8.549930%	2
C_5	Pipeline insulation	8.549930%	2
C_6	Specific resistance of soil	8.549930%	2
C_7	Salt of soil	8.549930%	2
C_8	Moisture of soil	8.549930%	2
C_9	Oxidation reduction potential | redox	8.549930%	2
C_{10}	PH of soil	8.549930%	2
C_{11}	Operating temperature	8.549930%	2

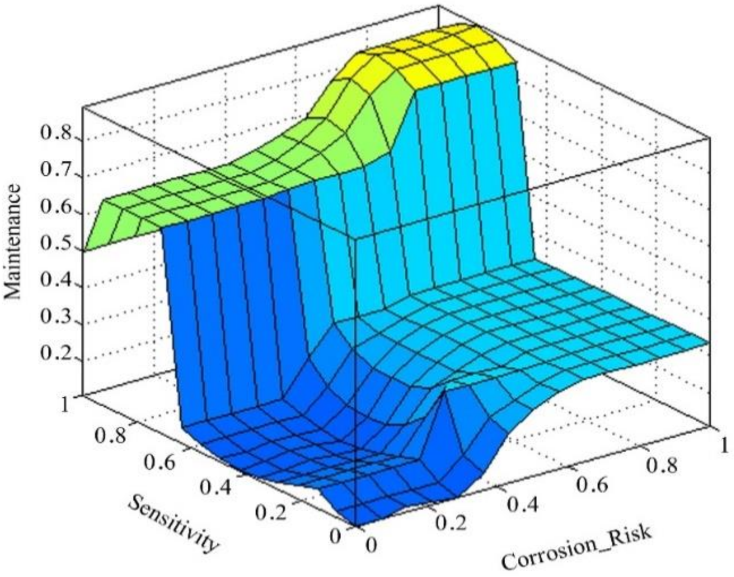


Figure 25 . Percentage of total changes in rating sweet natural gas pipelines criteria

5. Conclusion

In the research, the methodology is presented, for pairwise comparison and risk management caused by corrosion of natural gas pipelines. The conclusions, yielded by presented methodology are practicable and tangible, because of the fact that it presents suitable evaluation results by the least internal information, as its results obtain the capability for making comparison with other conditions and it reflects well the conditions of pipelines with the environmental consequences. The element “area of the affected area” has a major impact on the assessment. The distinction between the research and other studies carried out in the use of critical factors in an effective and comprehensive way and the use of all dimension of risk management and the inspection of influence and mutual impact of available components and presenting a systematic attitude to the issue of the gas industry’s exposure to corrosion. In other studies, failure to utilization of comprehensive components and simplifying internal variables, cause a reduction in precision and the compliance of assessed risk level. In previous studies, in the field of risk assessment, uncertainty of elite’s judgement in the result of assessment and risk priority have influenced immensely that this issue is one of the most significant challenges of risk assessment processes, which fuzzy logic has solved the uncertainty of elite’s opinions in the research. In fuzzy logic, a wide range has been considered for assessing risk, which has done more precise assessment. The relation between internal and external, as oral variables in the reflection of real condition, is more flexible and realistic; as a result, a proposed model could yield more reliable outputs. Hence, it is recommended, for reducing the risk level, caused by the corrosion of pipelines, a software, based on the presented model, has been designed and provided to this industry. Achieving to comprehensive information in natural gas pipelines is one of the restrictions in the current research; in addition, the utilization of elite community in national zone is another of the constraints in the study; as a result, developing into international elite community and applying more international standards in risk assessment domain and maintenance is offered in future studies. It is proposed to use a Bayesian network to estimate the probability of gas pipeline failure and compare the results with those of this study. For future studies, it is recommended to develop a comprehensive support system based on the above approach to gain a thorough understanding of the corrosion risk by implementing it at regular intervals. In addition, the following preventive measures are proposed to minimize the risk and its adverse consequences along the pipelines:

- It is proposed to investigate and compare the sensitivity based on indicators such as the age of the pipeline, the damage caused by corrosion, and the importance of pipeline availability.
- For internal corrosion, it is recommended to use a suitable coating and to check the coating of the pipes during construction. For external corrosion, it is recommended to use a coating of appropriate quality and a cathodic protection system.
- To reduce the impact in areas with a high population density, it is recommended to carry out patrols and inspections at a lower frequency.
- Automatic shut-off valves and sensitive pressure gauges were installed along the pipelines. The point where the valve was leaking was sealed.
- A crisis management plan was to be drawn up, including measures and plans for emergency situations and emergency call systems in the event of an explosion.

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