

Prioritization of Critical Corrosion Risk Factors in Natural Gas Pipelines Using the Full Consistency Method (FUCOM)

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ABSTRACT

Natural gas transmission systems play a vital role in ensuring energy supply, economic stability, and energy security. Due to rapid environmental changes, the expansion of transmission networks, and increasing operational complexities, risk management in natural gas pipelines has become increasingly important. Among various threats, corrosion is recognized as one of the most critical factors affecting pipeline integrity, potentially leading to significant economic, environmental, and safety consequences. Therefore, identifying and prioritizing the critical factors influencing corrosion is essential for improving managerial decision-making and planning preventive actions. The aim of this study is to identify and analyze the importance of critical corrosion factors in natural gas pipelines using the Full Consistency Method (FUCOM). The research was conducted during the fall of 2024 with the participation of experts and engineers in the gas pipeline sector who possessed at least ten years of professional experience. FUCOM was employed due to its ability to reduce the number of pairwise comparisons while improving the accuracy and consistency of criteria weighting. The results indicate that, in sour gas pipelines, factors such as pipeline age, inspection frequency, in-line inspection, coating and cathodic protection, inhibitor injection, and acidic gases are of primary importance. In sweet gas pipelines, monitoring and protection-related factors, including inspection frequency, in-line inspection, cathodic protection, and coating, were identified as the most influential factors. The findings provide valuable insights for enhancing corrosion risk management, developing effective maintenance strategies, and improving the reliability and integrity of natural gas transmission networks.

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1-Introduction

The world is currently facing significant challenges related to energy supply and energy security [1]. Rapid growth in global energy demand, geopolitical and economic instability, climate change, and disruptions in supply chains have highlighted the increasing importance of reliable and sustainable energy resources. In this context, natural gas has emerged as one of the most important energy carriers, playing a pivotal role in the energy transition and sustainable development. The safe and reliable delivery of natural gas is highly dependent on the effective operation of transmission and distribution pipeline networks [2].

Natural gas pipeline systems are among the most critical energy infrastructures worldwide due to their capability for continuous transportation, high transmission capacity, and operational reliability. Nevertheless, these infrastructures are exposed to a wide range of threats, among which corrosion is one of the most prevalent and critical. Previous studies have demonstrated that corrosion accounts for a substantial proportion of pipeline failures and industrial accidents [3]. Beyond reducing the service life of equipment and compromising pipeline structural integrity, corrosion can lead to severe economic losses, environmental damage, and safety-related consequences [4].

Given the potentially catastrophic consequences of pipeline failures, integrity management and corrosion control have become major priorities for oil and gas companies, governments, and other stakeholders in the energy sector [5]. In this regard, understanding the factors contributing to corrosion is essential for reducing accident rates and enhancing the reliability of gas transmission systems. Since pipeline-related risks are inherently complex, multidimensional, and characterized by nonlinear interactions among numerous variables, identifying critical factors and assessing their relative importance represent fundamental steps in effective risk management [3]. Consequently, increasing attention has been directed toward investigating the underlying factors that contribute to pipeline incidents and failures [1].

Addressing this challenge requires the accurate identification of the most influential factors associated with corrosion-related incidents. Therefore, explicit and reliable information regarding the prioritization of these factors is essential for supporting informed decision-making and improving safety management practices [3].

Although numerous studies have investigated factors affecting pipeline corrosion, the large number of influencing variables and limitations in available resources often make it impractical to address all factors simultaneously. As a result, some highly influential factors may receive insufficient attention

despite their critical importance. Therefore, identifying and prioritizing the most critical corrosion-related factors is essential for developing effective maintenance strategies, optimizing resource allocation, and improving managerial decision-making processes.

Accordingly, the present study aims to identify and analyze the critical factors influencing corrosion in natural gas pipelines using the Full Consistency Method (FUCOM). By reducing the number of pairwise comparisons required while maintaining a high level of consistency and accuracy in weighting criteria, FUCOM provides an efficient framework for prioritizing corrosion-related risk factors and supporting more effective corrosion risk management in natural gas transmission systems

2-Theoretical Background and Research Framework

2-1- Literature Review and Identification of Corrosion Risk Factors

Acid gases, particularly carbon dioxide (CO_2) and hydrogen sulfide (H_2S), are among the primary contributors to corrosion-related damage in natural gas transmission systems due to their highly corrosive nature [6]. During natural gas sweetening processes, these acidic components are removed from sour gas streams [7], thereby enhancing gas quality and supporting the role of natural gas as a relatively clean energy carrier [8]. Internal corrosion of steel pipelines is predominantly associated with the presence of CO_2 and H_2S in moist environments, where electrochemical reactions accelerate material degradation [9].

Protection against internal corrosion is commonly achieved through the application of corrosion inhibitors, whereas external corrosion of buried pipelines is generally mitigated using protective coatings and cathodic protection systems [10]. The reliability and long-term sustainability of energy transportation infrastructure depend heavily on the structural integrity of natural gas pipelines, which is continuously threatened by corrosion mechanisms. Consequently, the implementation of effective protective measures, including corrosion inhibitors, protective coatings, and cathodic protection systems, plays a critical role in maintaining pipeline safety and integrity [11].

Soil environmental conditions also exert a significant influence on the external corrosion behavior of buried pipelines. Physical and chemical soil properties, such as soil resistivity, moisture content, salinity, pH level, and oxidation–reduction potential, are widely recognized as key determinants of corrosion rates [12]. Furthermore, pipeline service life, coating quality, cathodic protection

performance, and operating conditions can substantially affect the severity of external corrosion [4,13].

In addition to environmental factors, operational conditions play an essential role in both the initiation and progression of corrosion processes. Elevated operating temperatures, internal pressure, fluid velocity, and the presence of free water can accelerate electrochemical corrosion reactions. Moreover, buried steel pipelines are inevitably subjected to residual internal stresses, welding-induced thermal stresses, and mechanical stresses resulting from soil movement and construction activities [14]. Increased temperature may further intensify the interaction between these stresses and corrosion mechanisms, thereby promoting crack initiation and propagation [15].

Given the progressive and cumulative nature of corrosion, periodic inspections and intelligent in-line inspections (ILI) are indispensable for monitoring pipeline conditions and detecting damaged or vulnerable sections at an early stage [16]. In addition, previous studies have highlighted the influence of microbial activity, stray electrical currents, and pipeline material quality on the likelihood and severity of corrosion.

Based on a systematic review of the literature, the factors influencing corrosion in natural gas pipelines can be broadly categorized into four major groups: environmental factors, operational factors, chemical factors, and protective factors. Accordingly, the most critical corrosion-related factors identified from previous studies are summarized in Table 1 and constitute the basis for the subsequent analysis conducted in this research.

Table 1. Critical Corrosion Risk Factors Identified for Natural Gas Pipelines.

Symbol	Critical Corrosion Factor	Sour Natural Gas	Sweet Natural Gas
C ₁	Pipeline Age	●	●
C ₂	Inspection Frequency	●	●
C ₃	In-Line Inspection (ILI)	●	●
C ₄	Cathodic Protection	●	●
C ₅	Pipeline Coating	●	●
C ₆	Soil Resistivity	●	●
C ₇	Soil Salinity	●	●
C ₈	Soil Moisture	●	●
C ₉	Soil Redox Potential	●	●
C ₁₀	Soil pH	●	●
C ₁₁	Operating Temperature	●	●
C ₁₂	H ₂ S	●	×
C ₁₃	CO ₂	●	×
C ₁₄	Corrosion Inhibitor Injection	●	×

2-2- Full Consistency Method (FUCOM)

The Full Consistency Method (FUCOM) is a multi-criteria decision-making (MCDM) technique developed by Pamučar for determining the relative weights of evaluation criteria. The method derives criteria weights through a minimal number of pairwise comparisons while simultaneously ensuring full consistency among decision-makers' preferences. Compared with conventional weighting approaches, FUCOM reduces the cognitive burden imposed on experts and improves the reliability and consistency of the weighting process. [17].

FUCOM is based on a single-objective nonlinear optimization model and is implemented through three sequential steps. In the first step, the evaluation criteria are ranked according to their relative importance based on expert judgments. The criteria are ordered from the most important to the least important criterion. When two or more criteria are considered equally important, they are assigned the same rank and denoted by an equality sign. This ranking process establishes the preference structure

required for the subsequent determination of comparative priorities and criteria weights [17].

$$C_j(1) > C_j(2) > \dots > C_j(k) \quad (1)$$

In the second step, following the ranking of criteria, the comparative priority between consecutive criteria is determined. In other words, the degree of preference of criterion $C_j(k)$ over criterion $(C_j(k+1))$ is elicited from experts. These comparative priority ratios are denoted by $\varphi_{k/k+1}$.

In the third step, the final weights of the criteria are calculated based on two main conditions: the consistency condition and the transitivity consistency condition. At this stage, the ratios of the final criterion weights must remain consistent with the comparative priorities determined in the previous step. Moreover, the relationships among weights must also satisfy the transitivity constraint.

Accordingly, the FUCOM nonlinear programming model is formulated as Model (2).

$$\begin{aligned}
& \text{Min } \chi \\
& \text{s.t.} \\
& \left| \frac{w_{j(k)}}{w_{j(k+1)}} - \varphi_{k/k+1} \right| \leq \chi, \forall j \\
& \left| \frac{w_{j(k)}}{w_{j(k+2)}} - \varphi_{k/k+1} \otimes \varphi_{k+1/k+2} \right| \leq \chi, \forall j \\
& \sum_{j=1}^n \omega_j = 1, \omega_j \geq 0, \forall j
\end{aligned}$$

Where ω_j denotes the final weight of criterion (j), $\varphi_{j/(j+1)}$ represents the comparative priority ratio between two consecutive criteria obtained from expert judgments, and χ denotes the deviation from full consistency. The objective function minimizes the maximum deviation from consistency requirements. The first set of constraints ensures that the ratios of the obtained weights remain consistent with the comparative priorities provided by experts. The second set of constraints guarantees transitivity consistency among the criteria weights. The final constraints ensure non-negativity of the weights and satisfy the normalization condition ($\sum \omega_j = 1$).

Compared with conventional multi-criteria decision-making methods such as the Analytic Hierarchy Process (AHP), the FUCOM approach requires a substantially lower number of pairwise comparisons. As a result, it reduces the computational complexity while simultaneously improving the consistency of expert judgments and minimizing potential inconsistency in the evaluation process.

3- Literature Review

A comprehensive review of the literature on pipeline corrosion highlights its critical role as one of the most significant degradation mechanisms affecting the service life, maintenance costs, and safety performance of fluid transmission systems. Moreover, prioritizing the factors influencing corrosion in deteriorated pipeline systems plays a key role in optimizing inspection and maintenance strategies. Accordingly, relevant studies in this field are reviewed below.

- Bakhtawar et al. [18] systematically examined the factors affecting time-to-failure and prioritized them using a fuzzy Analytic Hierarchy Process (AHP) based on magnitude of importance. Their results were validated through a Delphi-based expert survey, providing valuable insights for selecting features in time-dependent degradation modeling.
- Hussein Farh et al. [19] applied an extended fuzzy AHP approach to rank corrosion-related factors in water pipelines. Their study provided a structured overview of current research trends and identified gaps and limitations in the literature, highlighting directions for future research.
- Hageman et al. [20] developed a numerical model to predict corrosion rates under realistic operating

conditions by simulating electrochemical behavior. The study incorporated mass and charge transfer models, demonstrating that corrosion rates are strongly governed by the interplay between electrochemical reactions and mass transfer limitations.

- Hassan et al. [21] employed fuzzy and grey theories for risk assessment of oil pipelines. The results were used to prioritize risks and rank failure modes under different operational scenarios. A case study on a Nigerian petroleum pipeline system demonstrated the applicability and robustness of the proposed approach.

- Wei et al. [22] provided a critical review of microbial-induced corrosion (MIC) in natural gas pipelines. Their findings indicated that MIC is one of the dominant causes of pipeline failure and is highly localized and difficult to predict due to its complex behavior.

- Wasim, Milos B. Djuki [4] investigated external corrosion mechanisms in buried pipelines and associated failure modes. Their analysis of real failure cases showed that most pipeline failures result from the simultaneous interaction of multiple contributing factors.

- Wang et al. [23] proposed a hybrid risk assessment framework combining multi-criteria decision-making methods and fuzzy logic to enhance the reliability of complex industrial systems. Their findings demonstrated that the integrated approach improves risk evaluation accuracy and supports better prioritization of safety measures.

- Tang et al. [24] analyzed engineering failure mechanisms and identified key factors contributing to industrial system failures. Their study emphasized the role of material fatigue and environmental conditions, highlighting that multi-factor interactions significantly influence failure occurrence.

- Feng et al. [25] developed a Bayesian network-based model for risk assessment in process industries, particularly gas transmission systems. The model effectively captured complex interdependencies among risk factors and outperformed traditional simulation-based approaches in representing failure scenarios.

- Askari et al. [26] presented a comprehensive review of internal corrosion and cracking in oil and gas pipelines. Their results indicated that more than 50% of pipeline failures are related to internal corrosion, with the simultaneous presence of CO₂, H₂S, and water identified as the most critical accelerating factor.

Overall, the literature indicates that natural gas pipeline corrosion remains one of the most critical challenges in energy transmission systems, significantly affecting reliability, safety, and

operational cost. Existing studies have employed a wide range of approaches, including risk analysis models, fuzzy systems, Bayesian networks, and multi-criteria decision-making techniques, primarily focusing on identifying corrosion factors and ranking failure risks.

However, several research gaps remain. Most existing studies either focus on a specific pipeline type or provide generalized analyses without distinguishing between different operational conditions. In addition, the large number of influencing factors often leads to increased computational complexity and potential inconsistencies in expert judgments. Furthermore, the distinction between sour and sweet gas conditions and their impact on corrosion behavior has not been sufficiently addressed, despite clear industrial evidence of their differing corrosion mechanisms.

Moreover, although prior studies have identified corrosion-related factors, few have employed efficient weighting methods that simultaneously minimize pairwise comparisons while ensuring high consistency in expert judgments. To address these limitations, the present study utilizes the Full Consistency Method (FUCOM) to develop a robust and computationally efficient framework for prioritizing corrosion risk factors in natural gas pipelines.

The main contributions of this study are threefold: (i) distinguishing corrosion factor analysis between sour and sweet gas conditions; (ii) applying the FUCOM method to achieve minimal pairwise comparisons with high consistency; and (iii) proposing a structured framework for prioritizing critical corrosion factors to improve decision-making in pipeline integrity management and risk control. Consequently, this study extends existing literature and provides a reliable basis for enhancing corrosion risk assessment and improving the operational reliability of natural gas transmission networks.

4-Methodology

This study is applied in terms of its objective and descriptive-analytical in nature, conducted within a multi-criteria decision-making (MCDM) framework. The primary objective is to identify and analyze the importance of critical factors influencing corrosion in natural gas pipelines and to prioritize them under two

operating conditions, namely sour gas and sweet gas environments. To achieve this objective, the Full Consistency Method (FUCOM) is employed as a novel weighting technique for criteria prioritization. The statistical population of the study consists of experts and specialists in natural gas pipeline systems, operation, maintenance, and corrosion management, all of whom have at least ten years of professional experience in the oil and gas industry. A total of 30 valid expert responses were used in this study. The experts consisted of university faculty members and senior specialists in the natural gas industry, with professional experience ranging from 10 to 40 years (average: 18 years). Their expertise covered corrosion engineering, pipeline integrity, inspection, operation, and maintenance of natural gas transmission systems. A purposive sampling approach was used to select the experts, and their judgments were used as the primary basis for analysis and factor weighting.

In the first step, a systematic literature review was conducted based on scientific databases, standards, and prior studies to identify the key factors affecting pipeline corrosion. Ultimately, 14 critical factors were selected as input variables for the final analysis model. Subsequently, the FUCOM technique was applied to determine the weights and priorities of the identified factors. In this method, experts first ranked the factors according to their relative importance. Then, pairwise comparative priorities between consecutive factors were expressed in the form of preference ratios. In the third step, a nonlinear programming model was solved to estimate the final weights of the factors, ensuring maximum consistency between expert judgments and preference ratios, while satisfying the normalization constraint that the sum of weights equals one.

To enhance the robustness of the analysis, the factors were evaluated under two separate scenarios: sour gas pipelines and sweet gas pipelines. This distinction enabled a more detailed investigation of how corrosion-related factors behave under different operational environments.

Finally, based on the FUCOM results, the factors were ranked according to their relative importance, providing a solid basis for developing managerial strategies aimed at reducing corrosion risk in natural gas pipeline systems.

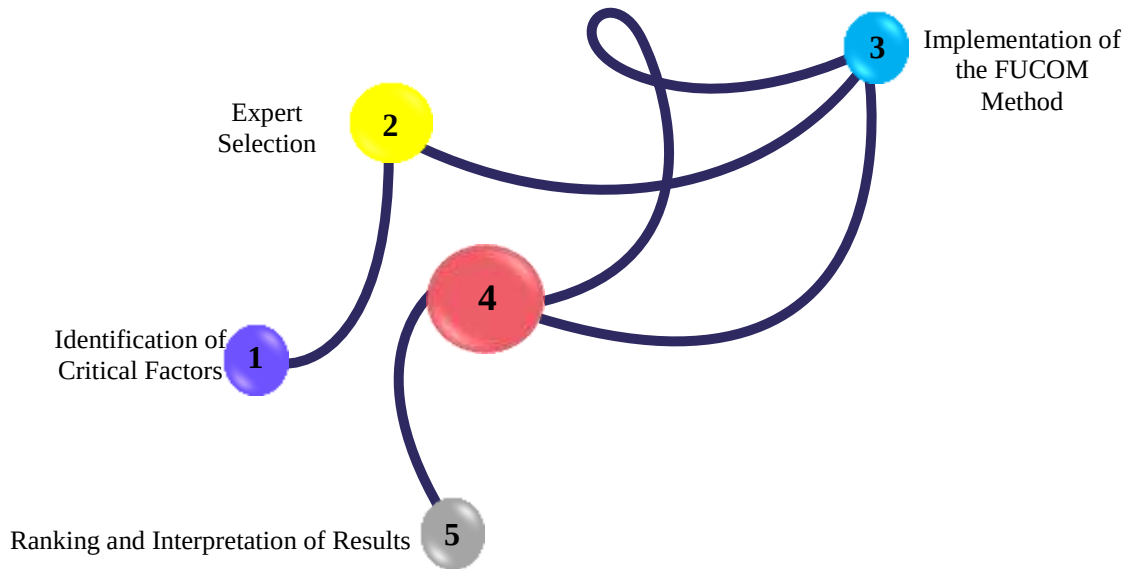


Fig. 1. Research Workflow

5-Findings

5-1-Sour Natural Gas

Another key component of the risk assessment analysis involves examining the weighting coefficients of each factor. The ranking of criteria,

based on expert judgments and their relative importance, is presented in Table 2. A nine-point scale was employed to determine the priority levels of the criteria, and the comparative priority ratios were derived according to expert preferences.

Table 2. Comparative Priorities of Critical Corrosion Factors in Natural Gas Pipelines as Elicited 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

Based on the obtained expert rankings of the criteria, the weighting coefficients W_k are computed in accordance with the corresponding comparative priority relationships.

$$\begin{aligned}
 \frac{w_{c1}}{w_{c2}} &= \frac{9}{8} = 1.125 & \frac{w_{c2}}{w_{c3}} &= \frac{8}{8} = 1 & \frac{w_{c3}}{w_{c5}} &= \frac{8}{7} = 1.143 & \frac{w_{c5}}{w_{c4}} &= \frac{7}{7} = 1 & \frac{w_{c4}}{w_{c14}} &= \frac{7}{6} = 1.167 \\
 \frac{w_{c14}}{w_{c13}} &= \frac{6}{6} = 1 & \frac{w_{c13}}{w_{c12}} &= \frac{6}{5} = 1.2 & \frac{w_{c12}}{w_{c9}} &= \frac{5}{5} = 1 & \frac{w_{c9}}{w_{c6}} &= \frac{5}{4} = 1.25 & \frac{w_{c6}}{w_{c8}} &= \frac{4}{4} = 1 \\
 \frac{w_{c8}}{w_{c11}} &= \frac{4}{3} = 1.33 & \frac{w_{c11}}{w_{c7}} &= \frac{3}{2} = 1.5 & \frac{w_{c7}}{w_{c10}} &= \frac{2}{1} = 2
 \end{aligned}$$

The remaining weighting coefficients are derived based on the mathematical transitivity condition as well as expert judgments, as presented below.

$$\begin{aligned}
 \frac{w_{c1}}{w_{c3}} &= \frac{w_{c1}}{w_{c2}} \times \frac{w_{c2}}{w_{c3}} = 1.25 \times 1 = 1.25 & \frac{w_{c2}}{w_{c5}} &= \frac{w_{c2}}{w_{c3}} \times \frac{w_{c3}}{w_{c5}} = 1 \times 1.143 = 1.143 & \frac{w_{c3}}{w_{c4}} &= \frac{w_{c3}}{w_{c5}} \times \frac{w_{c5}}{w_{c4}} = 1.143 \times 1 = 1.143 \\
 \frac{w_{c5}}{w_{c14}} &= \frac{w_{c5}}{w_{c4}} \times \frac{w_{c4}}{w_{c14}} = 1 \times 1.167 = 1.167 & \frac{w_{c4}}{w_{c13}} &= \frac{w_{c4}}{w_{c14}} \times \frac{w_{c14}}{w_{c13}} = 1.167 \times 1 = 1.167 & \frac{w_{c14}}{w_{c12}} &= \frac{w_{c14}}{w_{c13}} \times \frac{w_{c13}}{w_{c12}} = 1 \times 1.2 = 1.2 \\
 \frac{w_{c13}}{w_{c9}} &= \frac{w_{c13}}{w_{c12}} \times \frac{w_{c12}}{w_{c9}} = 1.2 \times 1 = 1.2 & \frac{w_{c12}}{w_{c6}} &= \frac{w_{c12}}{w_{c9}} \times \frac{w_{c9}}{w_{c6}} = 1 \times 1.25 = 1.25 & \frac{w_{c9}}{w_{c8}} &= \frac{w_{c9}}{w_{c6}} \times \frac{w_{c6}}{w_{c8}} = 1.25 \times 1 = 1.25 \\
 \frac{w_{c6}}{w_{c11}} &= \frac{w_{c6}}{w_{c8}} \times \frac{w_{c8}}{w_{c11}} = 1 \times 1.33 = 1.33 & \frac{w_{c8}}{w_{c7}} &= \frac{w_{c8}}{w_{c11}} \times \frac{w_{c11}}{w_{c7}} = 1.33 \times 1.5 = 1.995 & \frac{w_{c11}}{w_{c10}} &= \frac{w_{c11}}{w_{c7}} \times \frac{w_{c7}}{w_{c10}} = 1.5 \times 2 = 3
 \end{aligned}$$

According to the conducted pairwise comparisons, the mathematical model for determining the criteria weights was formulated as Equation (3).

$$\begin{aligned}
 &\text{Min } \chi \\
 &\text{s.t.} \\
 &\left| \frac{w_{c1}}{w_{c2}} - 1.125 \right| \leq \chi, \left| \frac{w_{c2}}{w_{c3}} - 1 \right| \leq \chi, \left| \frac{w_{c3}}{w_{c5}} - 1.143 \right| \leq \chi, \left| \frac{w_{c5}}{w_{c4}} - 1 \right| \leq \chi, \left| \frac{w_{c4}}{w_{c14}} - 1.167 \right| \leq \chi, \left| \frac{w_{c14}}{w_{c13}} - 1 \right| \leq \chi, \\
 &\left| \frac{w_{c13}}{w_{c12}} - 1.2 \right| \leq \chi, \left| \frac{w_{c12}}{w_{c9}} - 1 \right| \leq \chi, \left| \frac{w_{c9}}{w_{c6}} - 1.25 \right| \leq \chi, \left| \frac{w_{c6}}{w_{c8}} - 1 \right| \leq \chi, \left| \frac{w_{c8}}{w_{c11}} - 1.33 \right| \leq \chi, \left| \frac{w_{c11}}{w_{c7}} - 1.5 \right| \leq \chi, \\
 &\left| \frac{w_{c7}}{w_{c10}} - 2 \right| \leq \chi, \left| \frac{w_{c1}}{w_{c3}} - 1.25 \right| \leq \chi, \left| \frac{w_{c2}}{w_{c5}} - 1.143 \right| \leq \chi, \left| \frac{w_{c3}}{w_{c4}} - 1.143 \right| \leq \chi, \left| \frac{w_{c5}}{w_{c14}} - 1.167 \right| \leq \chi, \left| \frac{w_{c4}}{w_{c13}} - 1.167 \right| \leq \chi, \\
 &\left| \frac{w_{c14}}{w_{c12}} - 1.2 \right| \leq \chi, \left| \frac{w_{c13}}{w_{c9}} - 1.2 \right| \leq \chi, \left| \frac{w_{c12}}{w_{c6}} - 1.25 \right| \leq \chi, \left| \frac{w_{c9}}{w_{c8}} - 1.25 \right| \leq \chi, \left| \frac{w_{c6}}{w_{c11}} - 1.33 \right| \leq \chi, \left| \frac{w_{c8}}{w_{c7}} - 1.995 \right| \leq \chi, \\
 &\left| \frac{w_{c11}}{w_{c10}} - 3 \right| \leq \chi \\
 &\sum_{j=1}^{14} \omega_j = 1, \omega_j \geq 0, \forall j
 \end{aligned} \tag{3}$$

In Equation (3), w_{c1} , w_{c2} , ..., w_{c14} denote the weights of the identified corrosion risk factors, while (χ) represents the deviation from full consistency. The constraints are constructed according to the comparative priority ratios obtained from expert rankings and ensure both consistency and transitivity

conditions. Solving the model provides the optimal weights of the corrosion factors under the sour gas scenario.

The results obtained from solving the mathematical model using LINGO software are presented in Table 3. The ranking of criteria weights is illustrated in Figure 2.

Table 3. Weights of Corrosion Risk Assessment Criteria in Natural Gas Pipelines.

w_{c14}	w_{c13}	w_{c12}	w_{c11}	w_{c10}	w_{c9}	w_{c8}	w_{c7}	w_{c6}	w_{c5}	w_{c4}	w_{c3}	w_{c2}	w_{c1}
00.0796	00.0775	00.0642	00.0364	00.0121	00.0625	00.0498	00.0248	00.0498	00.0960	00.0924	00.1092	00.1135	00.1320

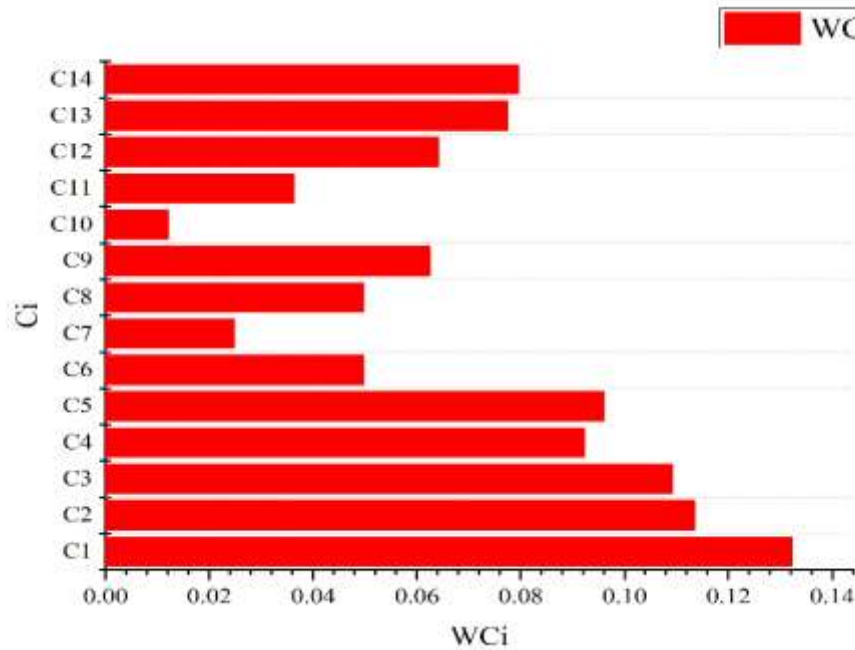


Fig. 2. Ranking of Criterion Weights for Corrosion Assessment in Natural Gas Pipelines.

5-2-Sweet Natural Gas

Based on the expert-derived priority rankings of the criteria, the weighting coefficients W_k are calculated in accordance with the corresponding comparative priority ratios.

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

The remaining weighting coefficients are calculated based on the mathematical transitivity condition and expert judgments, as described below.

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

Given the performed pairwise comparisons, the mathematical model for determining the criteria weights was formulated according to Equation (4).

$$\begin{array}{ll} \text{Min } \chi & (4) \\ \text{s.t.} & \\ \left| \frac{w_{c1}}{w_{c2}} - 1.125 \right| \leq \chi, \left| \frac{w_{c2}}{w_{c3}} - 1 \right| \leq \chi, \left| \frac{w_{c3}}{w_{c5}} - 1.143 \right| \leq \chi, \left| \frac{w_{c5}}{w_{c4}} - 1 \right| \leq \chi, \left| \frac{w_{c4}}{w_{c9}} - 1.4 \right| \leq \chi, \left| \frac{w_{c9}}{w_{c6}} - 1.25 \right| \leq \chi, \\ \left| \frac{w_{c6}}{w_{c8}} - 1 \right| \leq \chi, \left| \frac{w_{c8}}{w_{c11}} - 1.33 \right| \leq \chi, \left| \frac{w_{c11}}{w_{c7}} - 1.5 \right| \leq \chi, \left| \frac{w_{c7}}{w_{c10}} - 2 \right| \leq \chi, \end{array}$$

$$\begin{aligned} & \left| \frac{w_{c1}}{w_{c3}} - 1.25 \right| \leq \chi, \left| \frac{w_{c2}}{w_{c5}} - 1.143 \right| \leq \chi, \left| \frac{w_{c3}}{w_{c4}} - 1.143 \right| \leq \chi, \left| \frac{w_{c5}}{w_{c9}} - 1.4 \right| \leq \chi, \left| \frac{w_{c4}}{w_{c6}} - 1.75 \right| \leq \chi, \\ & \left| \frac{w_{c9}}{w_{c8}} - 1.25 \right| \leq \chi, \left| \frac{w_{c6}}{w_{c11}} - 1.33 \right| \leq \chi, \left| \frac{w_{c8}}{w_{c7}} - 1.995 \right| \leq \chi, \left| \frac{w_{c11}}{w_{c10}} - 3 \right| \leq \chi \\ & \sum_{j=1}^{14} \omega_j = 1, \omega_j \geq 0, \forall j \end{aligned}$$

The results obtained from solving the mathematical model using LINGO software are presented in Table 4, while the ranking of criterion weights is illustrated in Figure 3.

Table 4. Weights of Corrosion Risk Assessment Criteria for Sweet Natural Gas Pipelines.

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	0.06894	0.03455	0.06894	0.1206	0.1206	0.1379	0.1379	0.1551

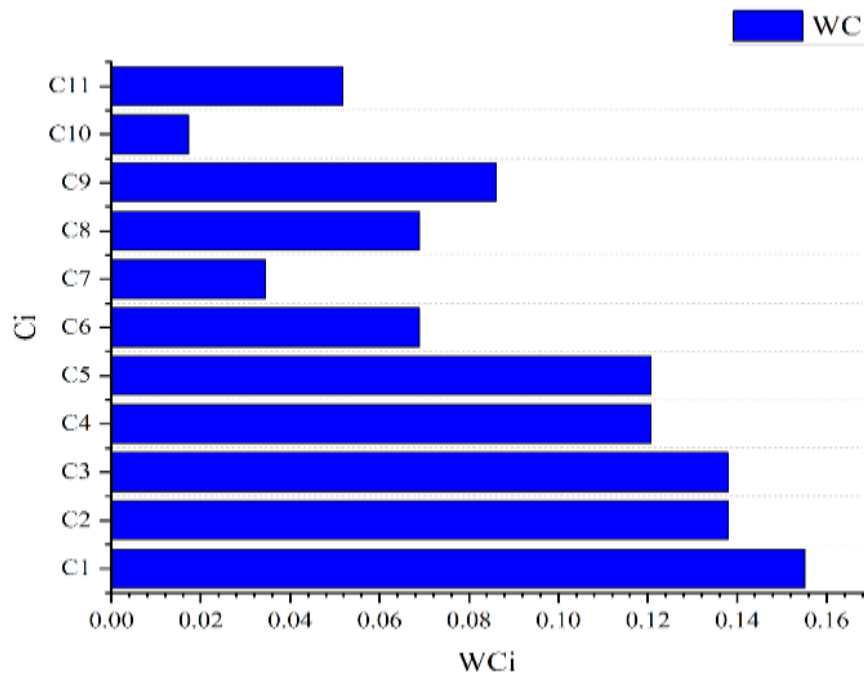


Fig. 3. Ranking of Criterion Weights for Corrosion Assessment in Sweet Natural Gas Pipelines.

- The results indicate that, in both sour and sweet gas conditions, factors such as pipeline age, inspection frequency, in-line inspection, coating, and cathodic protection exhibit the highest levels of importance, whereas pH is identified as the least significant factor among the critical variables.
 - In sweet gas pipelines, monitoring-related factors such as inspection frequency and in-line inspection, as well as protective measures including cathodic protection and pipeline coating, were found to have comparable levels of importance.
 - In sour gas conditions, following pipeline coating, factors such as corrosion inhibitor injection and the presence of acid gases demonstrate higher importance compared with other critical factors.
- The application of the FUCOM technique is associated with a reduced number of pairwise comparisons, thereby minimizing computational complexity. It is recommended that, in order to extend pipeline service life, measures such as inspection frequency, in-line inspection, coating, cathodic protection, and inhibitor injection be implemented at an optimal level.

6- Discussion and Conclusion

This study aimed to identify and prioritize the critical factors influencing corrosion in natural gas pipelines under both sour and sweet gas conditions using the Full Consistency Method (FUCOM). The obtained results indicate that pipeline corrosion is a multifactorial phenomenon strongly dependent on operational, environmental, and protective conditions, and cannot be attributed to a limited number of isolated factors.

The findings reveal that, in both sour and sweet gas environments, managerial and protective factors such as pipeline age, inspection frequency, in-line inspection, pipeline coating, and cathodic protection play a dominant role. The results obtained for sour gas pipelines differ noticeably from those for sweet gas pipelines. In sour gas conditions, chemical factors such as H_2S , CO_2 , and corrosion inhibitor injection received relatively high weights, reflecting the aggressive nature of acidic environments. This finding agrees with Askari et al. [26], who reported that the simultaneous presence of H_2S and CO_2 significantly accelerates internal corrosion and cracking processes in oil and gas pipelines.

In contrast, sweet gas pipelines were found to be more strongly influenced by monitoring and protection-related factors, including inspection frequency, in-line inspection, coating quality, and cathodic protection effectiveness. This observation is consistent with the findings of Wasim and Djukic [4], who emphasized that external corrosion failures are primarily controlled by protective systems and maintenance practices.

Furthermore, the high ranking of pipeline age in both operating environments is consistent with the deterioration-based prioritization framework proposed by Bakhtawar et al. [18], where infrastructure aging was identified as one of the most influential contributors to pipeline degradation and failure risk. This highlights the crucial importance of continuous monitoring and integrity management in reducing corrosion rates and enhancing system reliability.

In sour gas conditions, in addition to protective measures, the presence of acid gases such as CO₂ and H₂S, along with corrosion inhibitor injection, significantly influences corrosion severity. The validity of the obtained rankings is supported by previous pipeline failure and corrosion studies. Wasim and Djukic [4] reported that coating degradation, cathodic protection deficiencies, and aging infrastructure are among the primary contributors to external corrosion failures in oil and gas pipelines. Similarly, Askari et al. [26] identified the simultaneous presence of CO₂, H₂S, and water as one of the most critical causes of internal corrosion in gas pipelines. These observations are consistent with the present findings, where pipeline age, coating, cathodic protection, H₂S, CO₂, and inhibitor injection were ranked among the most influential corrosion factors. Therefore, the expert-based rankings obtained through FUCOM are supported by empirical evidence reported in previous pipeline failure investigations. This observation is consistent with the inherently aggressive nature of sour gas environments, where the interaction between chemical composition and operational conditions can markedly accelerate degradation processes. In contrast, in sweet gas conditions, environmental and protective factors are more influential, while chemical factors play a less dominant role. In these systems, the quality of coating and the effectiveness of cathodic protection become more critical in controlling corrosion. Overall, the results demonstrate that the FUCOM method enables accurate weighting of criteria with a minimal number of pairwise comparisons while ensuring a high level of consistency in expert judgments. Furthermore, the method effectively captures differences in factor importance under varying operational conditions and provides a robust framework for corrosion risk prioritization.

Based on these findings, the proposed approach can assist decision-makers in the natural gas industry in optimizing maintenance and inspection strategies by focusing on the most influential corrosion factors, thereby reducing the likelihood of corrosion-related failures.

6-1- Research Limitations

Despite the significant findings, this study has certain limitations. The data are primarily based on expert judgments, which may be subject to individual bias to some extent. Additionally, the present study focuses solely on prioritizing corrosion factors and does not include predictive modeling of corrosion rates or dynamic system behavior analysis.

6-2- Future Research Directions

To extend and enhance this research, future studies are recommended to adopt hybrid approaches. For instance, integrating FUCOM with methods such as DEMATEL or ANP could help identify causal relationships among corrosion factors. Moreover, future research may employ artificial intelligence, machine learning, or neural network-based models to enable not only prioritization but also accurate prediction of corrosion behavior under real operating conditions.

Furthermore, expanding field studies with a larger pool of experts from different industrial sectors can improve the robustness and generalizability of the results. Investigating the effects of varying climatic conditions, soil characteristics, and regional factors on pipeline corrosion is also suggested as an important research direction. Finally, developing an intelligent decision-support system for corrosion risk management is recommended to facilitate practical implementation in the oil and gas industry.

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