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Analysis of Corrosion Maintenance Scenarios for Natural Gas Pipelines Using Fuzzy Cognitive Mapping

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Abstract

Every country requires an efficient governance sector as a capable tool to realize its macro policies, enabling it to play a role in various industrial domains. It is expected that the managerial behaviors of the stakeholders in gas transmission pipelines align with the numerous developments occurring in the industry. The rapid and continuous changes of the present era have placed pipeline networks in a dynamic and variable environment, where risk management is of paramount importance to keep pace with these changes. Risk response must be comprehensively considered in corrosion management to ensure the sustainable operation of pipeline networks. In this regard, the analysis of corrosion maintenance system scenarios for natural gas pipelines, utilizing a fuzzy cognitive map, has been presented as a decision-making framework for risk management in pipeline corrosion. This study is applied in nature and employs a survey-exploratory data collection method, utilizing a deductive-inductive research approach. Participatory action research was conducted with the assistance of 30 engineering experts, including those specialized in metallurgy, who possess the necessary knowledge and experience with a minimum of 10 years in the field. Using a fuzzy cognitive map, scenarios within the maintenance system of natural gas pipelines were designed and developed. The proactive maintenance strategy achieved the highest degree of centrality in the gas industry. The proposed strategies can serve as a guide for policymakers in formulating a roadmap for the maintenance system of natural gas pipelines in the face of corrosion.

Keywords: Maintenance, Pipelines, Natural Gas, Corrosion, Fuzzy Cognitive Map.

1. Introduction

Gas is a valuable resource that accounts for more than 50% of the world's energy supply and is transported via pipelines. Steel, the most commonly used material for gas transmission pipelines, is highly susceptible to corrosion. Corrosion significantly impacts all sectors of the economy, particularly the gas industry. It can reduce the lifespan and structural integrity of pipelines. Therefore, controlling external corrosion on gas pipelines is essential to ensuring their integrity [1]. Various solutions are available to address this challenge [2]. The aging of pipelines leads to an increased risk of failure. Corrosion monitoring plays a crucial role in early detection and the adoption of preventive strategies, which significantly impact pipeline corrosion management [3]. Underground pipelines are constantly exposed to illegal interference, corrosion, and damage from external factors. The complexity of the underground environment and the high cost of continuous monitoring pose a serious threat to public safety and social stability. Traditional technologies for the prevention and control of underground pipeline incidents are currently unable to meet the growing demands of public safety [4]. To implement an effective rehabilitation program, it is necessary to evaluate various scenarios of the pipeline maintenance system.

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Different maintenance decisions alter corrosion risk, creating a dynamic aspect in corrosion analysis [5]. An effective method must be able to describe the relationship between variables under uncertainty [6]. Maintenance operations during the operation of pipeline networks require a significant portion of the budget [7]. Numerous studies have been conducted on pipeline maintenance systems [8]. The decision-making space for responding to corrosion is multi-dimensional and based on various indicators and criteria with differing levels of impact. Determining an effective strategy relies on expert judgment. Therefore, the aim of this study is to analyze maintenance system scenarios for the corrosion of natural gas pipelines using a fuzzy cognitive map. This research highlights the challenges of pipeline maintenance systems, which, compared to independent studies, achieves a synergistic effect by developing a structured classification based on studies focused on the corrosion of natural gas pipelines.

2. Research Background

The present study aims to review the research field with the goal of enhancing the effectiveness of the maintenance system for gas transmission pipelines and to conduct a dynamic analysis of maintenance scenarios in the modelling of pipeline corrosion response. The following sections will review the studies conducted in this area:

- Zhong et al. [9] presented a periodic maintenance model based on a dynamic Bayesian network. This model utilizes a recursive combined failure rate rule to accurately represent changes in system reliability over different maintenance intervals. The robustness of the model was validated through a pipeline case study. The results demonstrated that semi-annual maintenance could significantly reduce the probability of pipeline failure compared to annual maintenance.
- In the study by Zhang et al. [10], intelligent maintenance of natural gas pipeline valves in China was presented. The research examined the causes of failure, analyzed performance signals, and proposed strategies for the smart maintenance of natural gas pipeline valve systems.
- Fan et al. [11] optimized the reliability of the maintenance system for gas pipeline spare parts. A discrete Markov model was used to describe the state transition process. The optimization was performed using a genetic algorithm, and the effectiveness of the method was validated through a case study of a pipeline system in China.
- In the study by Hong et al. [12], modular equipment was developed for long-term maintenance planning to enhance the flexibility of the gas industry. A mixed-integer linear programming model was created to obtain the optimal strategy. The results showed that the utilization rate increased from 60% to 75%, providing a 10% higher economic benefit compared to traditional methods in gas field production when using modular equipment.
- In the study by Li et al. [13], a maintenance decision-making model for natural gas pipelines based on a Bayesian network was proposed. The costs of maintenance strategies were combined in an optimization function. Due to limitations in data records, some parameters in the Bayesian network were probabilistic and integrated using expert experience and fuzzy set theory. The case study confirmed the feasibility of the maintenance decision-making model.
- Phan et al. [14] presented an optimal maintenance model for aging steel bridges, based on reliability and corrosion risk. The bi-objective optimization model was applied to a steel bridge, aiming to minimize both the probability of risk and the total life cycle cost, including "initial construction costs and life cycle maintenance costs." A reliability-based sensitivity analysis was conducted on various factors related to the strength of the beams.
- Florian et al. [15] proposed a maintenance prediction model based on machine learning. The mathematical model incorporates investment costs and machine learning performance. An error matrix is utilized to quantify the costs associated with maintenance actions. Additionally, the mathematical model provides a cost-based quantitative method based on the receiver operating characteristic (ROC) curve of performance features.
- Rachman et al. [16] employed machine learning in pipeline integrity management. This paper provides a comprehensive review of the applications of machine learning in managing and processing data generated from Pipeline Integrity Management (PIM) activities. The study examines the role of machine learning in various elements of the PIM process, such as inspection, monitoring, and maintenance, as well as the aspects of machine learning techniques, including input types, preprocessing, learning algorithms, output metrics, and evaluation criteria used in each PIM element.
- Fu et al. [17] presented an optimization model for component allocation aimed at reducing maintenance costs with an economic motivation. The replacement in the system is conducted with the goal of minimizing maintenance costs over time. To this end, a mixed-integer nonlinear programming model was developed for optimal timing and allocation policies in the system. The expected maintenance costs per unit of time were analyzed. The results demonstrated the efficiency and applicability of the proposed model.
- In the article by Zakikhani et al. [18], a maintenance planning framework for external corrosion of gas transmission pipelines is proposed through an availability-based method. This framework is based on the

reliability specifications of the pipeline obtained from Monte Carlo simulations. The results indicated that a combination of maintenance actions was the most effective availability-based maintenance approach for the case study.

- Liu et al. [19] optimized the maintenance design for natural gas pipelines exposed to corrosion. The proposed multi-level strategy includes repaired Markov states (Level 1), maintenance timing (Level 2), and the number of maintenance activities throughout the pipeline's lifespan (Level 3). The optimization of the maintenance system for natural gas pipelines was carried out using a genetic algorithm approach.

Numerous researchers have been working to establish a framework for operationalizing a corrosion risk management system along with economic values in the gas industry. However, determining an effective maintenance strategy is essential for improving the safety of pipeline operations. The impact of strategies on the integrity of pipelines necessitates a systemic perspective on the gas industry's encounters with corrosion. This study aims to analyse the maintenance scenarios of corrosion in natural gas pipelines using fuzzy cognitive mapping to enhance the effectiveness and efficiency of the corrosion maintenance system through scenario analysis. An effective maintenance system requires the analysis of maintenance scenarios for pipelines. This study focuses on analysing maintenance scenarios in the modeling of corrosion in natural gas pipelines to enhance the effectiveness of the pipeline maintenance system. The developed approaches in this research will provide tangible benefits for the National Gas Company in managing corrosion. Emphasizing effective strategies in response to corrosion will improve the safety of the pipelines.

3. Research Methodology

It appears that there are limited publications in the field of scenario analysis for maintenance systems, and focusing on these articles is essential for providing engineering solutions for this industry. Accordingly, the present study analyses the maintenance scenarios of corrosion in natural gas pipelines using Fuzzy Cognitive Mapping (FCM). The method employed in this research is developmental-applicative in nature and, from the perspective of data collection, is descriptive-survey based. This study was conducted during the winter of 2023, and the collected information was derived from prior research or expert opinions. The data collection tool used in this research was a questionnaire. Participatory action research was conducted with the assistance of 30 engineering experts, such as metallurgists, who possessed the necessary knowledge and experience, with a minimum of 10 years of expertise. In order to structure the factors influencing corrosion within the framework of causal relationships, important components were identified using fuzzy cognitive mapping methodology, and scenarios along with themes, effects, and indicators were presented. Based on the results obtained from the relational map, scenarios were designed. The stages of research implementation include the processes of "concept identification, fuzzy cognitive mapping, scenario modelling, and analysis of the fuzzy cognitive map scenarios," as illustrated in Figure 1.

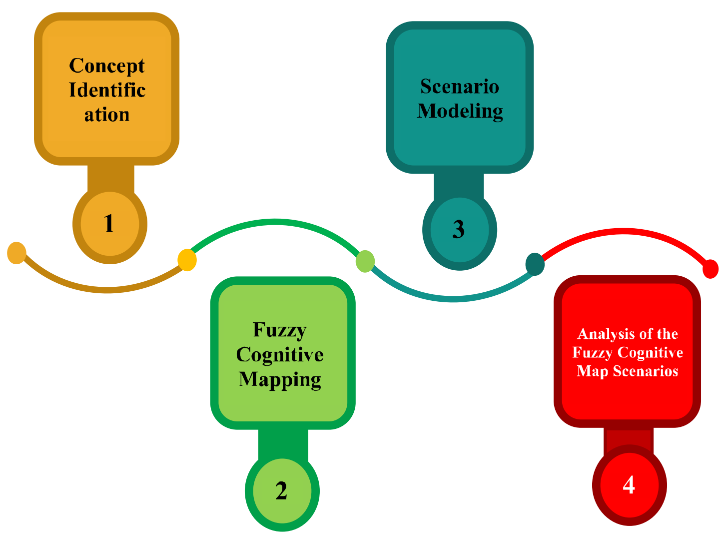

Figure 1. Research Stages Flowchart.

Fuzzy cognitive maps are employed for quantitative modelling based on the knowledge and experience of experts. This map is an efficient fuzzy graph that describes the nodes, concepts, and edges, representing the relationships between concepts with degrees of connection through fuzzy numbers in the interval $[-1,1]$. A fuzzy cognitive map is derived from an adjacency matrix. Centrality serves as a measure to determine the importance of a node within the cognitive map, calculated by the sum of the number of concepts influenced by C_j and the number of concepts dependent on C_j [20].

Scenario modelling is a strategic tool based on long-term time horizons and is utilized for the immediate design of solutions considering future uncertainties [21]. The approach employed in this research is the Global Business Network (GBN) methodology, which involves scenario development that includes the following stages: "defining the main focus of the subject for scenario development, identifying key factors in the immediate environment, recognizing the driving forces of changes and future uncertainties, selecting the logic of the scenarios, and developing characteristics for each scenario" [22].

4. Analysis of Findings

The present study encompasses three main categories: "Inspection, Maintenance, and Corrosion." Inspection is a component of pipeline integrity management. The governing regulations for inspection are the safety regulations pertaining to pipelines. Internal inspection of pipelines is typically conducted using non-destructive testing techniques and other technologies [23]. Maintenance activities are performed to update and maintain pipelines in optimal conditions. Maintenance methods for pipelines vary [23]. The execution of maintenance activities is essential based on the corrosion conditions identified through pipeline inspections [24]. The concepts of "Inspection, Maintenance, and Corrosion." have been identified based on expert opinions and the necessity of inspection and maintenance in corrosion risk management in studies [23-26]. The overall schematic of the designed model is presented in Figure 2, in accordance with the results of the conducted research.

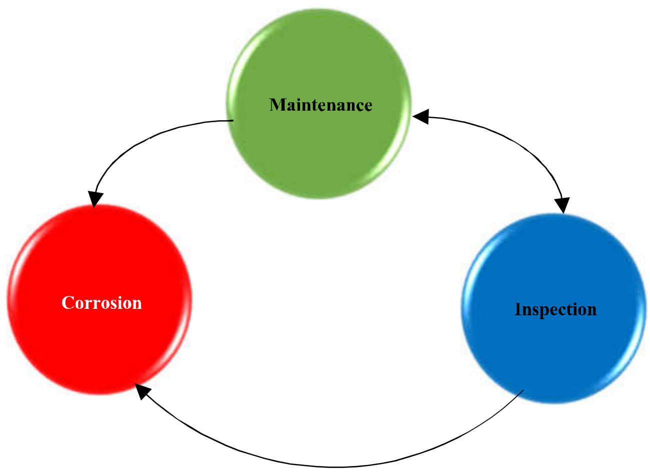

Figure 2. Overview of the Relationships Between Inspection and Maintenance in Addressing Corrosion Risk

The overall connections in the designed model indicate that in the network of natural gas pipelines, ineffective inspection can lead to undetected corrosion and ultimately result in pipeline leaks. Furthermore, a lack of maintenance contributes to the failure to control corrosion, culminating in pipeline leaks. The inspection process is utilized for "risk reduction, predicting incidents and failures, and prevention" of such events. The ability to detect faults through inspection can vary in effectiveness. If corrosion increases and energy losses occur, the reasons may lie within the service and maintenance processes. In this case, the organization's strategy may be inappropriate or not executed correctly.

4-1. Concept Identification

Identifying the key indicators and uncertainties of the natural gas pipeline maintenance system scenarios was conducted through a meta-synthesis approach, based on studies such as Iqbal et al. [28], Li et al. [29], Abdulnaser et al. [30], and Heidary et al. [31], along with expert opinions. Meta-synthesis is a method in which research is synthesized to yield a new interpretation of the collection of studies. This interpretation can lead to a more comprehensive explanation of the phenomenon under investigation or may generate new theories to elucidate the examined phenomenon [32]. Since the goal is to investigate the maintenance indicators of natural gas pipelines, only articles relevant to this section were selected. The obtained indicators are presented in Table 1, accompanied by expert opinions, in order to effectively reduce systemic complexity.

Table 1. Concept Coding and Indicators of Corrosion in the Natural Gas Pipeline Maintenance System Using a Meta-Synthesis Approach.

Indicators	Type of Consequence	Consequences		Failure Modes	Concept
Repair or replacement of components Repair or replacement of pipelines Maintenance of the cathodic protection system (components, pipelines) Repair or replacement of pipeline coatings Gound/direct drainage Injection of inhibitors Major repairs Time-based maintenance Performance-based maintenance Condition-based maintenance Risk-based maintenance	Transportaion Interuption Effect Safety/Health Effect Enviromental/Ecological Effect Equipment Maintenance Effect	Fire Explosion Intoxication Enviroment Pollution	Flammability Explosivity Toxicity Volatility Pollution	Leak/Rupture Release of oil & Gas Dispersion of oil & gas	Corrosion Maintenance Inspection

In the maintenance system for pipelines, the following strategies are implemented: "injection of inhibitors, repair or replacement of pipeline coatings, maintenance of cathodic protection systems (Cathodic protection part / Cathodic protection line), direct/ground drainage for stray current, and replacement of pipelines due to external corrosion" [29]. The inspection strategies for pipelines include " Magnetic Flux Leakage Inspection (MFL), Ultrasonic Inspection (UT), Eddy Current (EC) Technique, Eddy Current Pulsed Thermography (ECPT), Radiography Testing (RT), and Acoustic Emission (AE) Inspection " [33]. The proposed strategies in the context of maintenance for pipelines are as follows [28]:

- In the strategy of Corrective Maintenance (CM) (the first generation of maintenance strategies), activities commence after an incident and failure occur. This strategy seems logical to employ when there is an adequate profit margin. However, in the gas industry, given the nature of energy transportation, this approach may not be feasible due to potential environmental and financial repercussions. Furthermore, the establishment of repair equipment can be quite costly and requires a significant amount of time. Nevertheless, this strategy cannot be entirely disregarded, as it constitutes an integral part of maintenance policies in the event of a failure.
- In the strategy of Preventive Maintenance (PM) (the second generation of maintenance strategies), operations such as "inspection, repair, or replacement" are carried out based on recommendations, guidelines, past experiences, and the review of historical data. In this strategy, significant attention is given to the time intervals and the operational performance of the system. The policies include considerations based on "age, periodic/time, and failure/repair limitations."
- Predictive Maintenance / Condition-Based Maintenance (the third generation of maintenance strategies) encompasses a set of activities that continuously monitor the components of a system during operation, assess the technical condition of the system, and identify the wear of components and system failures. Based on the obtained data, it determines maintenance activities and the timing of their implementation. An effective maintenance strategy aims to eliminate the causes and roots of failures, serving as a replacement for preventive and predictive maintenance strategies. The strategy of Condition-Based Maintenance focuses on improving the status of equipment by eliminating all causes of failures. This maintenance strategy aims to make maintenance decisions based on the collected measurement data. A prerequisite for implementing this strategy is the existence of an integrated system for data collection and a set of measurement tools to assess performance during operation. Through continuous evaluation, abnormal conditions can be detected, allowing for necessary actions to be taken in a timely manner, if needed, prior to the occurrence of failures.
- The strategy of Proactive Maintenance (the fourth generation of maintenance strategies) is also known as preventive maintenance policies. The primary objective of this strategy is to prevent and reduce root causes before failures occur, with an emphasis on the significant consequences of these causes and the more vulnerable areas and components of the infrastructure. The fundamental difference between predictive maintenance and proactive maintenance policies lies in the focus of decision-making; proactive maintenance emphasizes the condition of the equipment while subsequently considering the consequences of failures. This strategy is risk-based. Risk-Based Maintenance is a relatively new approach for pipelines. Integrity management can be considered as condition-based maintenance. The inspection and maintenance strategy is a need-based approach for prioritizing an inspection and maintenance program based on risk ranking, which assists managers in making informed decisions without adversely affecting the community.

4-2. Fuzzy Cognitive Mapping of Concepts

To construct a fuzzy cognitive map, expert opinions or time-series data can be utilized; in the present study, expert opinions were employed. The identified concepts were presented to the research experts in the form of a pairwise comparison matrix, and they were asked to rate the concepts based on a five-point Likert scale. Given that the obtained information was verbal and not interpretable, symmetric triangular fuzzy numbers were converted in the adjacency matrix to construct the fuzzy cognitive maps according to the averaging approach. The aggregated adjacency matrix of expert opinions is shown in Table (2), and the drawn fuzzy cognitive map, created using the NetDraw software, is depicted in Figure (3). The calculation of the degree of centrality of the maintenance system indicators for the pipelines is presented in Table (3) using the UCINET software.

Table 2. Adjacency Matrix of Extracted Trends in the Maintenance System.

	Corrosion	Protective Measures	Pipeline Monitoring	Time-Based Maintenance	Inspection	Performance-Based Maintenance	Risk-Based Maintenance	Repair or Replacement of Components	Repair or Replacement of Pipelines	Major Repairs	Condition-Based Maintenance
Corrosion	0	0.9	0.88	0.82	0.91	0.84	0.89	0.7	0.72	0.78	0.895
Protective Measures	0.9	0	0.78	0.72	0.81	0.74	0.79	0.6	0.62	0.68	0.69
Pipeline Monitoring	0.88	0	0	0	0	0	0	0	0	0	0
Time-Based Maintenance	0.82	0	0	0	0	0	0	0	0	0	0
Inspection	0.91	0	0	0	0	0	0	0	0	0	0
Performance-Based Maintenance	0.84	0	0	0	0	0	0	0	0	0	0
Risk-Based Maintenance	0.9	0	0	0	0	0	0	0	0	0	0
Repair or Replacement of Components	0.71	0	0	0	0	0	0	0	0	0	0
Repair or Replacement of Pipelines	0.74	0	0	0	0	0	0	0	0	0	0
Major Repairs	0.78	0	0	0	0	0	0	0	0	0	0
Condition-Based Maintenance	0.905	0	0	0	0	0	0	0	0	0	0

In this study, the risk-based maintenance system aims to identify the degradation level at a critical threshold or under significant environmental shock. When defects such as cracks arise due to corrosion, pipelines become significantly more vulnerable to damage from environmental shocks, leading to a marked increase in the likelihood of ruptures. The degradation level in this research is based on inspection and maintenance results, assessed by the parameters of "soil corrosiveness, presence of acidic gases, existence of stray currents, coating failures, and failure of cathodic protection systems."

Table 3. Indegree, Outdegree, and Centrality of the Pipeline Maintenance System.

Centrality	Indegree	Outdegree		
16.72	8.385	8.335	Corrosion	C_1
8.23	0.900	7.330	Protective Measures	C_2
2.54	1.660	0.880	Pipeline Monitoring	C_3
2.36	1.540	0.820	Time-Based Maintenance	C_4
2.63	1.720	0.910	Inspection	C_5
2.42	1.580	0.840	Performance-Based Maintenance	C_6
2.58	1.680	0.900	Risk-Based Maintenance	C_7
2.01	1.300	0.710	Repair or Replacement of Components	C_8
2.08	1.340	0.740	Repair or Replacement of Pipelines	C_9
2.24	1.460	0.780	Major Repairs	C_{10}
2.49	1.585	0.905	Condition-Based Maintenance	C_{11}

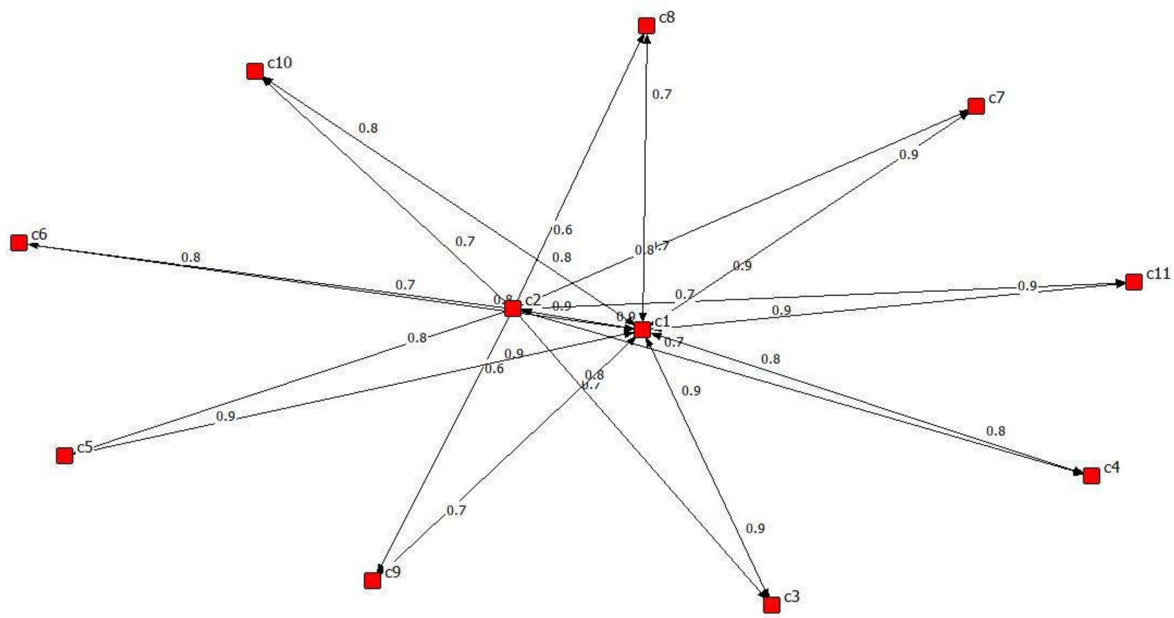

Figure 3. Fuzzy Cognitive Map of the Natural Gas Pipeline Corrosion Maintenance System.

The results from Table (3) and Figure (3) indicate that the factors "inspection, risk-based maintenance, pipeline monitoring, and condition-based maintenance" are **the most responsive**, respectively. In contrast, the factor "protective measures" is **the least responsive**. The factors "protective measures, inspection, condition-based maintenance, risk-based maintenance, and pipeline monitoring" have **the highest levels of influence**, while the factor "repair or replacement of components" has **the lowest level of influence**. Factors such as "protective measures, inspection, risk-based maintenance, and pipeline monitoring," with high centrality scores, are considered **important factors within the system**.

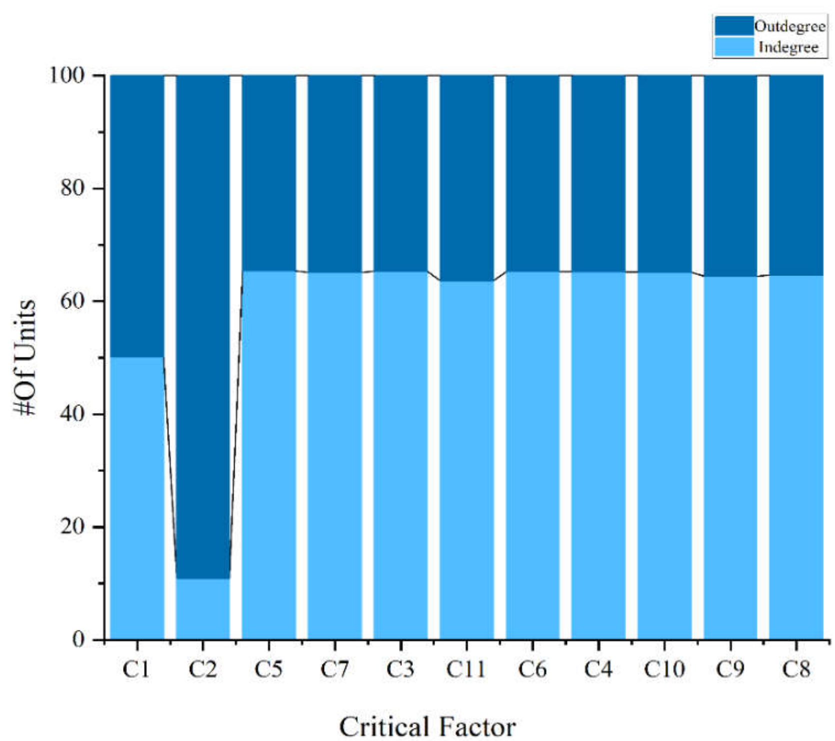

Figure 4. Stacked Bar Chart of the Drivers of the Natural Gas Pipeline Maintenance System.

The maintenance strategy in the gas industry is considered the most cost-effective when maintenance actions are performed before failures occur. This finding reinforces the effectiveness of the risk-based corrosion maintenance strategy highlighted in this study. The corrosion communication matrix based on the inspection approach, analyzed using grounded theory, is presented in Table (4), and the fuzzy cognitive map is shown in Figure (5).

Table 4. Adjacency Matrix of Extracted Trends.

	echnical inspection h tools or by huma	duction of corrosio risk	orrosion prediction	Corrosion prevention	Corrosion detection speed	Inspection skill	High cost of corrosion	Extended pipeline lifespan	Attention to safety and the	Lack of budget and	Proactive maintenance	Lack of action	Inspection program	Corrosion	Energy loss
Technical inspection with tools or by human	0	0	0	0	0	0	0	0	0.78	0	0	0	0	0.82	0.72
Reduction of corrosion risk	0.81	0	0	0	0	0	0	0	0	0	0.83	0	0.70	0	0
Corrosion prediction	0.80	0	0	0	0	0	0	0	0	0	0.82	0	0.45	0	0
Corrosion prevention	0.82	0	0	0	0	0	0	0	0	0	0.84	0	0.38	0	0
Corrosion detection speed	0.80	0.85	0	0.85	0	0	0	0	0	0	0.85	0	0.65	0	0
Inspection skill	0.85	0	0.85	0.75	0	0	0	0	0	0	0.85	0.25	0.65	0	0
High cost of corrosion	0.78	0	0	0	0	0	0	0	0	0	0.82	0	0.45	0	0
Extended pipeline lifespan	0.89	-0.82	0	0	0	0	0	0	0	0	0.81	0.35	0.65	0	0
Attention to safety and the environment	0.72	0	0	0.82	0	0	0	0	0	0	0.77	0	0.52	0	0
Lack of budget and inspection resources	-0.62	0	-0.88	-0.80	0	0	0	0	0	0	-0.7	0.90	-0.45	0	0
Proactive maintenance	0	0	0	0	0.52	0	0	0	0.8	0	0	0	0	0.9	0.75
Lack of action	0	0	0	0	-0.62	0	0	0	0.12	0	0	0	0	-0.42	0.12
Inspection program	0	0	0	0	0.52	0	0	0	0..77	0	0	0	0	0.72	0.67
Corrosion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Energy loss	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

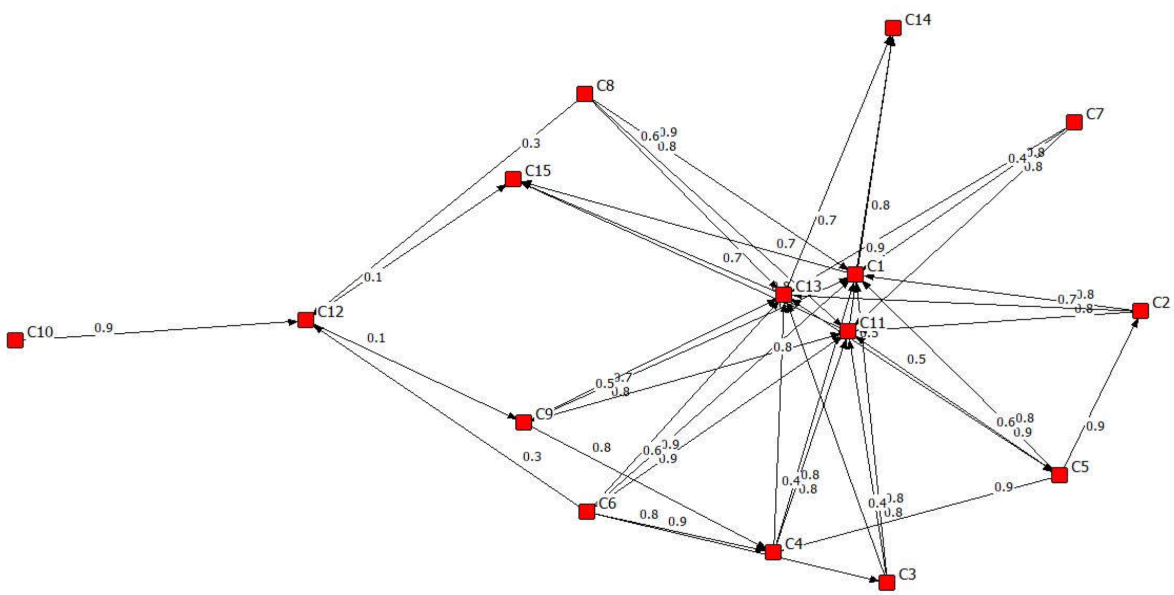

Figure 5. Fuzzy Cognitive Map of Natural Gas Pipeline Inspection.

The analyses conducted, including centrality indicators such as capacity of responsiveness, ability to affect, and pivotal index, are presented in Table 5 using UCINET software.

Table 5. Indegree, Outdegree, and Centrality of Pipeline Inspection.

Centrality	Indegree	Outdegree		
8.17	5.850	2.320	Technical inspection with tools or by human	C_1
2.37	0.030	2.340	Reduction of corrosion risk	C_2
2.04	-0.030	2.070	Corrosion prediction	C_3
3.66	1.620	2.040	Corrosion prevention	C_4
4.42	0.420	4.000	Corrosion detection speed	C_5
4.2	0.000	4.200	Inspection skill	C_6
2.05	0.000	2.050	High cost of corrosion	C_7
1.88	0.000	1.880	Extended pipeline lifespan	C_8
4.53	1.700	2.830	Attention to safety and the environment	C_9
-2.55	0.000	-2.550	Lack of budget and inspection resources	C_{10}
8.86	5.890	2.970	Proactive maintenance	C_{11}
0.7	1.500	-0.800	Lack of action	C_{12}
5.91	4.000	1.910	Inspection program	C_{13}
2.02	2.020	0.000	Corrosion	C_{14}
2.26	2.260	0.000	Energy loss	C_{15}

The results in Table 6 indicate that the factor "proactive maintenance" is identified as the most significant factor influencing inspection, while "Lack of budget and inspection resources" is recognized as the least important factor affecting inspection. Although the budget factor holds considerable importance in the industry, its scarcity cannot justify the lack of inspection and maintenance in high-risk industries such as the gas sector. The stacked bar chart illustrating the factors influencing the inspection of natural gas pipelines is presented in Figure 6.

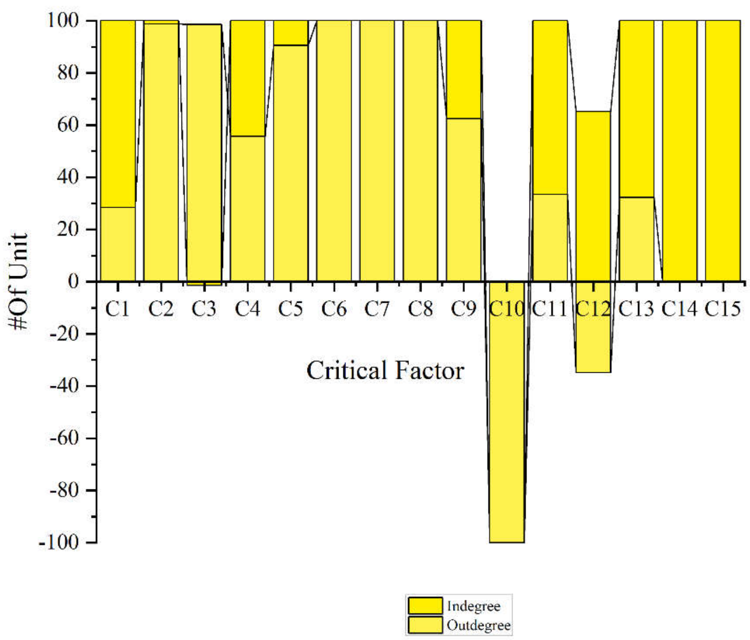

Figure 6. Stacked bar chart of the factors influencing the inspection of natural gas pipelines.

4-3. Scenario Modelling

Foresight, leveraging scientific principles, aims to understand the scope of the future and select the most critical decisions. Using fuzzy cognitive maps among trends, scenarios are developed. Initial analysis indicated that the element "protective measures" plays a key role in the causal mapping of the corrosion maintenance system. To assess the impacts of controlling risk-driving factors on other mapping elements, scenarios corresponding to various policies were defined. In the first scenario, the level of activity for all mapping elements was considered to be one. The degree of activity for elements ranges between [0 and 1]. A value of zero indicates that the element in question is absent in a specific iteration within the system, while a value of one signifies that the element in question exists with the highest degree of activity (relative frequency) in the system. By observing the results of the first category scenarios, a new scenario corresponding to the policy of controlling the key mapping elements was defined. In this scenario, four key elements with the highest degree of centrality were selected as control variables, and in the initial state representation, the corresponding values of these elements were considered to be zero. The second scenario was then designed based on the complete control of these specified elements.

4-4. Analysis of the Fuzzy Cognitive Map Scenario

The simulation results based on the first scenario vector indicated that after the first iteration, the mapping network reached a stable state, with the values corresponding to the steady-state vector of the risk mapping elements presented in Figure (7). The values of the steady-state vector for the mapping elements suggest that the changes made had minimal impact compared to the other elements, and the final values of the elements were largely similar to the final values in the first scenario, where no variables were under control. Based on the results of the first scenario, a new scenario corresponding to the policy of controlling the key mapping elements was defined. The results obtained from the second scenario, as shown in Figure (8), indicated that the simultaneous control of the four key variables still did not affect the elements subjected to control. An examination of the elements revealed that the primary reason for this was related to the origin of corrosion risk.

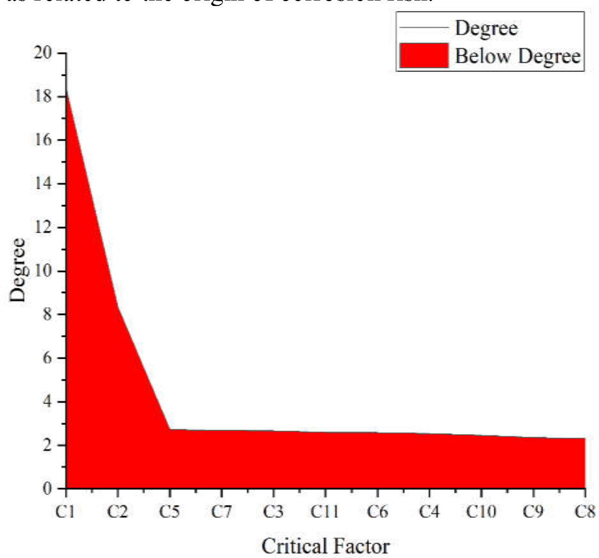

Figure 7. Values of the steady-state vector of elements in Scenario 1.

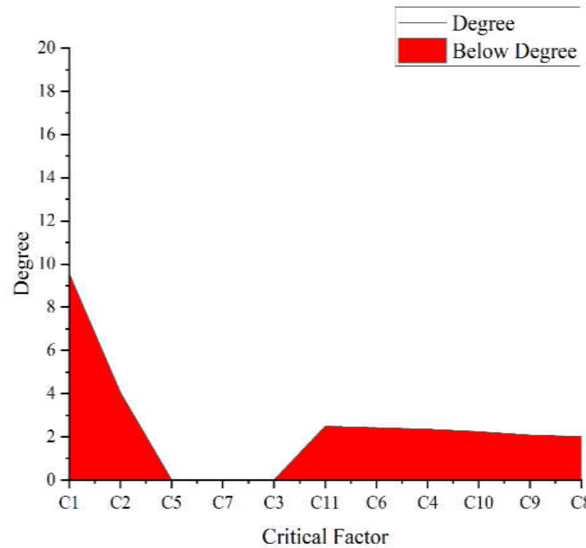

Figure 8. Values of the steady-state vector of elements in Scenario 1.

5. Conclusion

Natural gas is considered a vital artery for the economy and industry. The gas industry, due to the extensive consumption of natural gas and the widespread network of pipeline transmission lines, requires heightened monitoring. Failure to oversee these lines can lead to incidents such as fires, explosions, and significant damages. Understanding the scenarios of the maintenance system is crucial for preventing incidents and optimizing process performance in this industry. Therefore, this paper analyzes the scenarios of the corrosion maintenance system for natural gas pipelines using fuzzy cognitive mapping. Adapting sustainable development practices in this industry is of particular importance. Achieving sustainability requires strategic approaches and cannot be realized through minor actions alone. Thus, identifying the components influencing sustainability adaptation in the gas industry and analyzing them within the framework of causal relationships is a vital and fundamental step toward energy sustainability.

The use of quantitative approaches, such as regression analysis, necessitates the reduction of factors and consequently overlooks some variable effects. Qualitative approaches also face challenges. Moreover, conceptual models rarely provide policymakers with actionable guidance for development. Therefore, fuzzy cognitive mapping presents itself as a suitable approach. This research, utilizing fuzzy cognitive mapping, enables a quantitative analysis of the issue for policymakers. Based on the results of the causal structure of the maintenance system, the factors "protective measures, inspection, condition-based maintenance, risk-based maintenance, and pipeline monitoring" exhibit the highest levels of influence, while the factors "inspection, risk-based maintenance, pipeline monitoring, and condition-based maintenance" demonstrate the greatest levels of responsiveness within the maintenance system. Given the developed scenario, the identified factors "protective measures, inspection, risk-based maintenance, and pipeline monitoring" should be prioritized by the gas industry. By altering and enhancing the status of these factors, the maintenance system for natural gas pipelines will also improve. Protective measures include "pipeline coatings, cathodic protection systems, and corrosion inhibitor injection."

In conclusion, it is recommended that gas industry managers focus on strategies based on the factors "protective measures, inspection, risk-based maintenance, and pipeline monitoring" to achieve sustainability. For the development of research, it is suggested that researchers utilize the dynamic characteristics of this approach in problem analysis using a fitting function. Additionally, it is recommended to examine the impact of stray currents within the maintenance system. The final recommendation is to incorporate environmental factors into the sustainability model to enhance the gas industry.

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