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Economic Assessment of Improper Performance Indicators and Pipeline Spill Intensity for Repair and Substitution (Case Study)

Ramin Ghaffari[1], Nikbakhsh Javadian[2*]

[1]MSc, Socio-Economic Systems Engineering, Mazandaran University of Science and Technology, Mazandaran, Iran.
[2]Assistant Professor, Mazandaran University of Science and Technology, Mazandaran, Iran.
*Corresponding author

Abstract

This study evaluates the economic implications of improper performance indicators and pipeline spill intensity for determining the most cost-effective solution between repair and substitution. Employing the Muhlbauer risk assessment technique, this research grades critical indicators such as human error, design flaws, and spill intensity. A uniform annual cost (UAC) method is used to compare the economic viability of repair versus substitution. Findings reveal that the improper performance index is significantly influenced by design-phase deficiencies, while higher spill intensity scores correlate with increased safety risks, particularly in high-population-density areas. Furthermore, corrosion and external factors in specific pipeline sections exacerbate risks, with substitution emerging as the safer, cost-effective alternative due to extended lifespan and minimized environmental hazards. Despite close cost proximity between repair and substitution, substitution is recommended for enhanced reliability. The study highlights the necessity of localizing the Muhlbauer model for Iranian pipeline conditions and extending its application to oil and petroleum pipelines. This approach can optimize resource allocation, minimize risk, and ensure operational efficiency.

Keywords: Pipeline Risk Assessment, Economic Analysis, Improper Performance Index, Spill Intensity, Muhlbauer Technique.

Introduction

Since gas is an endowment with limited resources, it must be accurately and precisely used. Pipelines are widely used in the natural gas transportation process. However, pipeline leakage may be a substantial threat to individuals, properties, and the environment [1], [2], [3], [4].

However, some internal or external factors, such as corrosion, natural force hazards, damage caused by third parties, and improper performance may be incidents causing accidents in pipeline systems with potentially adverse consequences for society, the economy, and the environment, including the main supply chains [5].

Gas loss may occur through pipelines or some points in these lines, which may cause leakage or explosion due to many reasons leading to economic losses caused by gas waste and pipeline repair costs, and or loss of life in populated areas where pipelines pass. Therefore, it is necessary to find these risky areas, and assessment of the risk rate of these areas plays an effective and vital role in reducing these losses. However, accurate reduction in this risk requires making the right decision to overcome probable defects. In this case, not only the risk is reduced in terms of safety and environmental aspects but also is cost-effective and useful for the gas Company. On average, more than 60% of a gas company's budget is annually spent on pipeline repair, maintenance, and restoration, so the cost of various projects in this sector can be reduced by using common techniques in engineering economics and investing this cost in the construction of other pipelines.

Many studies have been done on this topic. For instance, Rui Xiao improved the failure modeling for gas pipelines and compared the RSF and COX models with other models explaining that Cox and RSF models provide insights into the effect of covariates on pipeline failure, informing decisions about pipeline construction, inspection, and maintenance activities. The findings show that the statistical COX model overestimates the failure age due to its limited potential for capturing failure nonlinearity, while other machine learning models underestimate the failure age because they cannot handle the dataset censoring [6].

Population density is one of the factors affecting the spill intensity and risk rate of gas pipelines.

Yunabo assessed the quantitative risk of a natural gas pipeline considering areas with high population and created two models: (1) a failure probability model based on the improved historical failure and disaster derivation probabilities and (2) a risk consequence model that considers potential direct and indirect losses based on the probability of disaster evolution. He finally compares these models with traditional models and concludes that the new assessment technique can effectively identify the high-consequence areas and achieve more reasonable results [7].

Ke Shan assessed the failure probability of gas transmission pipelines based on historical failure-related data and modification factors and suggested to use of modification factors to modify baseline failure frequency modification [8].

Also, Siler-Evans (2014) conducted a study on the analysis of pipeline accidents in the United States from 1968 to 2009 and concluded fatality of incidents has been reduced while financial losses have increased over these years [10].

Ahmadreza Feli (2011) carried out the economic assessment of various techniques for gas exports to China. In this research, he compared the economic status of natural gas transmission through four transmission methods (pipeline, gas-to-liquid conversion and transmitting it by liquid gas carriage ships, compressing natural gas in specific ships and transmitting them to destination, and converting gas to gas hydrate sold particles and transporting them with the ship to destination). Finally, it is concluded that the liquid gas technique has the lowest cost followed by pipelines and gas hydrate techniques in the second, and third ranks, respectively [5].

All previous related studies have been done on risk assessment in pipeline failure, and just extracted the risk value and chowed the risky areas. Also, these studies have considered the pipeline division criterion as a static variable, so their risk values may not be precise. On the contrary, the present study has bused dynamic techniques for pipeline division, and the studied pipeline has been divided into 688 sections to present a more accurate assessment of all points and sections in the route. Also, after determining risky points and their causes, the obtained solutions are economically examined and evaluated in the areas in which, the risk rate can be reduced with some changes. In this way, the process can be done at a lower cost. Therefore, this study aims to economic assessment of improper performance indicators and pipeline spill intensity with long life regarding repair and substitution.

Method

The research method for risk assessment is based on the Muhlbauer technique then the steps for grading indicators and criteria of this method are described. In terms of economic assessment, also the uniform annual cost was selected as the proper model for this study.

Ken Muhlbauer Technique [11]

In this technique, all important conditions and activities affecting pipeline safety are given numerical scores, so that all substantial parameters and variables are considered for each section of pipeline and these variables are given coefficients. The coefficient is measured based on the available statistical data and engineering judgments.

Four general indicators are considered for determining the parameters required for the risk assessment process: third-party risk potential index, human-error index, design index, and corrosion index.

In general, the mentioned indicators are matched with different types of probable failures in the pipeline. Each selected index reflects a part of information about the background of the pipeline and occurred incidents.

Regarding the options selected in the index, a numerical value is achieved for valuing the considered index. Four numerical values are obtained for four indicators, and these values are summed up and a final numerical value is presented at the end which is called cumulative index. This numerical value is used in the next part in which, risks' potential is assessed. In the second part, a precise analysis is done of the potential effects and consequences of each defect that occurred in the pipeline. The product's properties, operational conditions, and location of the pipeline are considered to achieve the consequence factor, which is called spill effect factor or spill effect, and includes acute and chronic effects of risks caused by spilling the product existing in the pipeline. The final risk value is measured by summing up the value obtained from the mentioned indexes and dividing it by the spill effects factor obtained in the second step.

Consequences

Assessment of incidents' consequences is the most critical phase in risk calculations. A number is given to each consequence or incident to have a criterion for spending cost on preventing that incident. However, the important point is that scarce resources are available for creating a safe system and decreasing the risk. Therefore, it must be considered in measuring the probability of an incident occurrence that the allocated resources are used optimally. The lost capital can be assessed quantitatively in most cases. For instance, it is possible to measure the following values when a pipeline bursts and causes fire and explosion: lost gas, cost of repair and substitution of defective pieces, extra costs caused by interrupted transmission service, the cost of destruction in buildings, machinery, environment cleansing, and other environmental costs. Humans are who do these analyses and computations in the first method.

Improper Performance Index

Although human error is one of the most critical aspects of hazards, it is hard to measure. Finding the wrong behaviors of individuals can be a substantial case in incident prevention plans. This index assesses the probability of errors occurring in the pipeline due to errors by staff and practitioners working in the design, construction, operation, and maintenance phases of the pipeline. The design and planning phases are not mainly documented, so they cannot be simply assessed. The scores of this phase are reported in Table 1.

Table 1. Variables of improper performance criterion in the design phase

Finding hazard	4
Probability of MOP[1]	12
Safety systems	10
Selection of substances	2
Revision	2
Sum	30

In the construction phase of assessment, some signs must be observed to ensure the pipeline is constructed accurately. These signs include revising and inspecting the quality of construction (Table 2).

Table 2. Grading the criterion of improper performance in the construction phase

Inspection	10
Substances and materials	2
Welding and fittings	2
Pipeline backfill	2
Transportation and maintenance	2
Insulation	2
Sum	20

[1] Maximum Operation Pressure

Incorrect performance in the operation phase

In the operation phase, the error may cause fast defects because staff are regularly working with valves, compressors, and other facilities. In this phase, human error prevention is emphasized instead of human error detection, so the grading process is done as follows.

Table 3. Grading the criterion of incorrect operation in the operation phase

Guidelines and standards	7
Control data and connections	3
Medical test	2
Safety plans	2
Assessments, maps, archive	5
Education	10
Mechanical prevention of error	6
Sum	35

Maintenance and Repair Index

Incorrect repair is one of the factors triggered by personal mistakes causing the incidence of different levels of errors in system operation. Lack of proper repair management, incorrect guidelines, lack of accuracy of repairers, and personal mistakes may directly or indirectly create errors and incidents in the pipeline. The maximum score of this phase equals 15, and grading is done based on the documentation of repair and operational records and data (0-2), creating planning and constant schedule for repairs (0-3), and some repair guidelines with practical aspects (0-10).

Spill Intensity Index

The spill intensity index is the consequence of the hazards that may occur in pipeline incidences and affect the health of people and the environment. This index serves as a negative option concerning the score of final risk. The spill intensity index underpins the grading pipeline failure and emphasizes asking what is the effective potential of a pipeline spill. The answer depends on two factors of the pipeline's conditions: A) the product, and B) the surrounding environment.

Table 4. Grading the criterion of product hazards

Acute hazards	Flammability (Nf)	0-4
	Reactivity (Nr)	0-4
	Product’s toxicity (Nh)	0-4
Reportable hazards (RQ[2])		0-10

[2] Reportable Spill Quantity

In the pipelines of gas and liquid products, flammability, reactivity, and toxicity are considered reportable hazards. The reportable hazards would reduce life span and have long-term effects triggered by the contamination in living spaces when such products are released from pipelines. Although it may occur that contents exited from the pipeline do not lead to toxicity and flame, the damages caused by such contaminations have fatal effects on the lives of people and society, whose consequences are imminent and potential. The CERCLA[3] classification standard is used to grade this parameter (Figure 1).

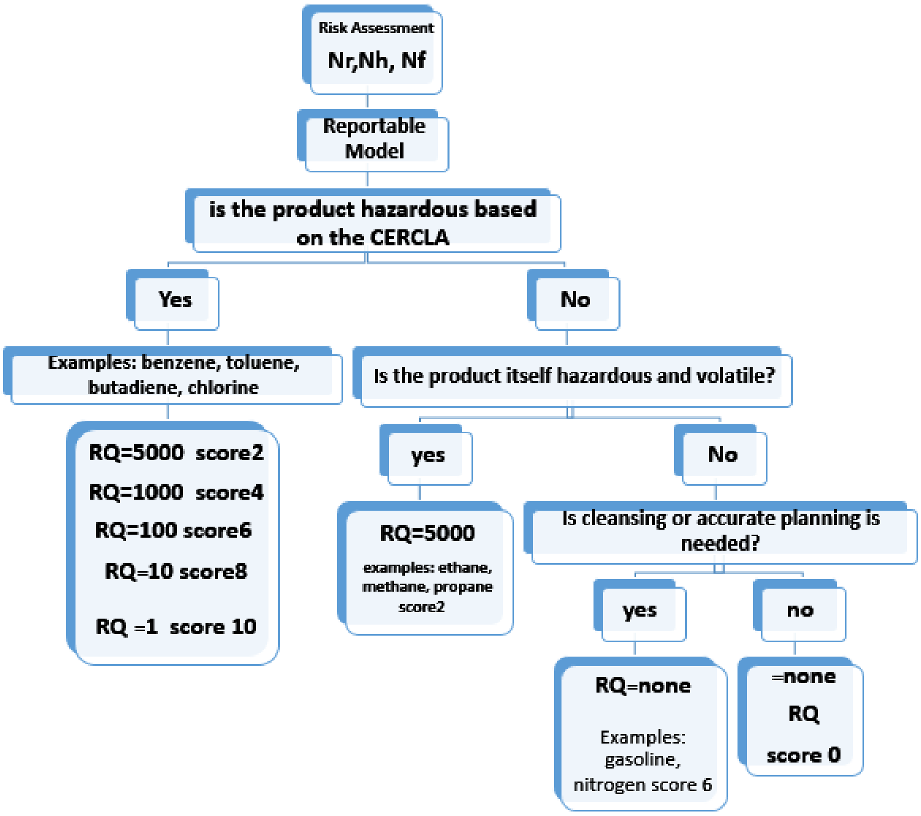

Figure 1. Algorithm of risk assessment for reportable hazards

Economic assessment

The uniform annual cost method was used for economic assessment in this study. In Equivalent Uniform Annual Cost / Benefit (EUAC/EUAB), costs and benefits are converted to uniform annual receipts and payments, so it is called uniform annual cost and or uniform annual benefit. It is not required to make the life of projects equivalent in this method.

If 0<EUAC, the project is cost-effective and it is not cost-effective if 0>EUAC. To compare several projects, the uniform annual cost of each project is measured and the projects with the lowest annual costs would be the most cost-effective.

In this method, P represents the present value of money (the principle of money), F indicates the future value of money (the principle and interest of money), and A shows the number of equivalent costs and benefits in all periods.

[3] Comprehensive Environmental Response, Compensation and Liability Act.

Since the life of a replaced pipeline differs from its life after repair, the uniform annual method is used. Also, the income obtained after the repair or substitution of the pipeline is equivalent and just costs are different, so the uniform annual method is used. This process is measured in three ways:

1. In the first method, P is converted to uniform annual cost by using the A/P factor, and SV value is converted using the A/F factor then SV value with a negative sign is added to uniform annual cost. i.e.:

EUAC= P (A/P, i%, n) – SV (A/F, i%, n)

where P indicates the present value of money, F shows the future value of money, and A is the number of equivalent costs or benefits in all periods. SV represents scrap value.

2. In the second method, the present value of SV is first measured, deducted from the initial cost, and then the present value is converted to a uniform annual cost. It means that:

EUAC = [P- SV (A/P, i%, n)] (A/F, i%, n).

3. In the third method, the SV and initial cost difference are determined and then multiplied by the A/P factor, and then the value obtained from SV multiplied by the minimum interest rate is added to it. it means that:

EUAC = (P – SV) (A/P, i%, n) + SV (i).

Findings

Incorrect Performance Index

Incorrect Performance Criterion in the Design Phase

According to the conducted assessment on the criterion of hazard detection, score 2 is considered for all areas of the pipeline.

In terms of MOP probability, experts assume that it is not possible to reach maximum operation pressure for the whole length of the pipeline; hence, a score of 5 is considered for this part.

In terms of safety systems, only one safety system exists in the route of this pipeline. Hence, score 3 is given to this sub-criterion for the whole route.

In terms of selecting substances, score 2 is considered for the whole area regarding the control documents required for the system's component information.

In terms of inspection and control, score 1 is given to this part of the pipeline based on the experts' ideas.

Incorrect Performance in the Construction Phase

In terms of inspection criterion, score 7 is considered for the whole parts of this route due to relative surveillance over the pipeline route.

In terms of substances and materials, the whole areas take a score of 2 since the best and highest-quality substances and materials are used in the executive processes of the pipeline.

In the case of welding and fittings, experts give a score of 1 to this part.

In terms of backfill, score 1 is considered for this sub-criterion throughout the route because the backfill has an average situation over the pipeline length.

In the case of transportation and maintenance, score 1 is considered because experts assume that pipeline construction time, transportation and maintenance of substances especially pipes, and maintenance of electrodes and other cases are approximately suitable.

In terms of insulation, score 1 is given to this sub-criterion regarding the average quality of installation and execution of coating, particularly the insulation of welded installations.

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Incorrect Performance in Operation

In terms of the guideline, score 4 has been given to this sub-criterion in the whole route of the pipeline regarding the conducted assessments.

In the case of data and SCADA[4] communication criterion, the system of the studied pipeline has a controlled electron system and SCADA communications and since all activities are observed in the pipeline, score 2 is given to this sub-criterion.

In terms of medical tests, score 2 is given to this sub-criterion regarding the regular medical tests for pipeline staff every six months.

In the case of safety, score 1 is considered for this sub-criterion in all areas based on the conducted assessments and experts' opinions.

In the case of inspection, maps, and archives, score 2 is considered for all the areas regarding the incomplete system of archives and maps.

In the case of education, a score of 5 out of 10 is considered for this sub-criterion based on the studies conducted on educational plans for mitigating human error and documents reviewed in the HSE department.

In terms of mechanical prevention of error, a maximum score of 6 is given to this variable regarding the full installation of mechanical devices to prevent operator error and the installation of different types of automatic valves in the pipeline route.

Incorrect Performance in the Maintenance and Repair Phase

According to conducted studies, a score of 1 out of 2 is considered for documentation, a score of 2 (out of 3) is given for planning, and a score of 5 (out of 10) is considered for guidelines in the repair and maintenance phase throughout the whole areas.

Spill Intensity Index

The criterion of product hazards is divided into two sub-criteria acute and reportable hazards.

In acute hazards, methane is the gas used in pipelines. In terms of flammability, methane has Nf=4; therefore, the score of flammability equals 4 for all areas. In terms of reactivity, it has Nr=0; therefore, the score of reactivity equals 0 for all areas. In terms of toxicity, the Nh rate of methane equals 1; hence, a score of 1 is given to all areas. Therefore, score 5 is considered for the whole pipeline regarding the acute hazards.

The criterion of reportable hazards, RQ equals 5000 for methane has a score of 2 based on the CERCLA Standard, which classified substances based on the RQ (effects of the spilled mass unit to the surrounding environment based on Pound). Therefore, score 2 is given to this sub-criterion throughout the pipeline.

In terms of spill volume, score 1 is given to this variable throughout the pipeline since the type X60 of pipe is used that has moderate toughness.

The criteria of product transmission and distribution take a score of 3 since the methane's spill rate is measured equal to 100000 pounds 10 minutes after pipeline failure and the molecular weight of methane equals 16 based on the risk assessment table.

The score given to exposed individuals throughout the pipeline has been shown in the following chart based on the available data and visiting the pipeline route (Figure 2).

[4] Supervisory Control and Data Acquisition

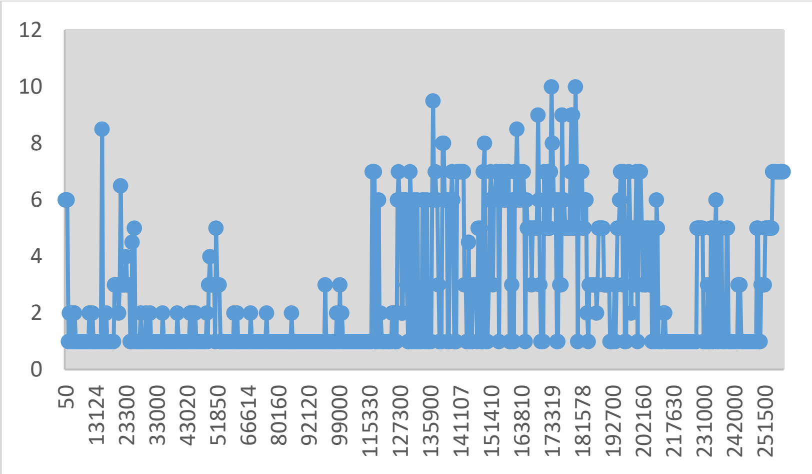

Figure 2. The score is given to exposed individuals

Results of Economic Assessment

The uniform cost method has been used for economic assessment. According to the results of the risk assessment, subsurface corrosion is seen in the 670-m route of the pipeline. Assessments indicate that the 200-meter length of this range needs substitution and repair to solve this problem. Therefore, the conducted economic assessment is based on this 200-m length and the relevant costs are also measured based on this length. According to the last report published by the Central Bank during research time (June 2015), the interest rate equals 20%. Since substitution and repair required 55 days and 90 days, respectively, the interest rate of substitution and repair equals 3% and 5%, respectively. Moreover, the life span of the pipeline after repair equals 15 years, while the life span of the pipeline equals 40 years after substitution. The costs of repair and substitution of the pipeline are reported in Table 5.

Table 5. Cost of repair and substitution

	Substitution	Repair
Raw substances	8	18
Worker cost	12	21
Cost of waste gas	346.5	237.5
Cost of pipe	260	-
A scrap of pipe	44.4	-
Extra cost	7.5	3
Interest rate	3%	5%

In the following methods, $EUAC_S$ indicates a uniform annual cost of substitution and $EUAC_R$ represents a uniform annual cost of repair. The p-value equals the sum of the costs reported in the Table above.

1. First method

$EUAC_S =$ 634*(A/P,3%,40) – 44.4*(A/F,3%,40)

$EUAC_S =$ 634*(0.04326) – 44.4*(0.01326) = 26.838

$EUAC_R =$ 279.5*(A/P,5%,15) – 0

$EUAC_R =$ 179.5*(0.09634) = 26.927 $\Rightarrow$ $EUAC_S < EUAC_R$

As it is seen, the cost of pipeline substitution is less than the cost of its repair. Hence, pipeline substitution is more cost-effective than pipeline repair.

2. Second method:

The second method cannot be used in our considered study because no scrap exists in the repair case.

3. Third method:

$EUAC_S = (634 - 44.4) * (A/P,3\%,40) + 44.4(0.03)$

$EUAC_S = 25.506 + 1.332 = 26.838$

$EUAC_R = 279.5 * (A/P,5\%,15) = 26.927 \quad \Rightarrow EUAC_S < EUAC_R$

This method indicates that the cost of substitution is less than the repair cost, so it is more cost-effective than repair.

Conclusion

This study aims to do an economic assessment of incorrect performance indicators and pipeline spill intensity with a high life span regarding repair or substitution. The results showed that the scores given to the incorrect performance index indicate adverse situations, and the most critical problem and damage occur in the design phase. Also, unlike the previous index, the higher the score given to the spill intensity index, the lower the safety and the higher the hazard risk will be. The most effective factor that increases this criterion includes crowded and valuable districts, which leads to higher risk that requires more precision and accuracy in these areas.

Also, the results indicated that 173+319km is located in a rural area that has a high activity level and population density. Moreover, the pipeline has severe corrosion in the underground of this area. The 180+820km area is located in an urban district that has a high activity level and forest situation. Moreover, the pipeline passes under the park and the area with high population density. The 173+584km area is located in the urban district that has a high activity level and population density. Moreover, severe corrosion is seen on the external surface of the pipes located in this district. The 136+250km is located in an urban area with high population density. Also, the pipeline passes by some sensitive places, such as hospitals. The area of 175+760km has a high risk of hazards since the gas pipeline passes through a populated district with villa houses. The activity level is very high in this area. The 168+160km of urban district has a high population density. Also, the soil coverage does not have a desired condition. The 178+660km is located in the area with villa houses adjacent to the forest and has a high population density. The 17+550km is located under the road with asphalt pavement where the activity level is high, so the pipeline passes by a town with high population density. Also, the gas pipeline passes by the intersection with the oil pipeline.

In terms of economic assessment, the results showed that the cost of substitution of damaged sections is less than the cost of repair, so pipeline substitution is suggested since the income of the pipeline is the same in both repair and substitution cases. Although the assessment indicates that costs of repair and substitution are highly close to each other and no significant difference is seen between them, it may be said that substitution or repair can be done in equal conditions. However, it must be considered that pipeline substitution is more secure for the route in terms of safety and environment.

Since the algorithm and weighing method available in this pilot are based on the presented foreign model, this model must be localized by correcting the weights given to each item and the risk calculation algorithm. In this case, risk values can be determined precisely and this model can be matched with specific conditions of transmission pipelines in Iran. Also, it is recommended to use the proposed model for assessing the risk of oil and petrol pipelines.

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