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Risk analysis of city gas networks using multi-criteria decision making method and AHP hierarchical analysis

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Abstract

Transporting energy carriers through pipelines is one of the most economical methods of transporting natural gas, oil, and petroleum products, which are associated with many risks through road and rail transport fleets. Conducting environmental risk assessment studies is a step in the direction of identifying, analyzing, and classifying risk-generating factors and thus reducing the possibility of adverse consequences and controlling the potential risks of such projects in order to protect the environment. This study has been done with the aim of providing a model to assess the environmental risk of gas transmission projects. In this research, in order to achieve the goal, a combination of the indexing system method and the decision matrix process is proposed. By using this integrated method, it is possible to classify, quantify, and prioritize all kinds of environmental risks in gas transmission pipeline projects based on the determined indicators and criteria. Based on the risk assessment, the results showed that the two failure cases of gas cylinder breakage and network and connection leakage are the most critical failure modes based on risk.

Keywords: Risk Management, Decision Matrix, Gas Industry, Energy Transport, AHP

1 Introduction

The gas enters the CGS main city gas station through the transmission pipeline with a maximum pressure of 700-1000 psi and a minimum pressure of 300-350 psi, and after reducing the pressure to 250 psi, the gas enters the pressure reduction stations through the main lines of the supply network or the belt loop. In the city, it becomes TBS and after reducing the pressure to 60 psi, it enters the distribution network lines (Figure 1) and through the branch lines, gas is supplied to the consumers after reducing the pressure by the regulator according to the type and amount of consumption (Sekhavati and Jalilzadeh, 2022).

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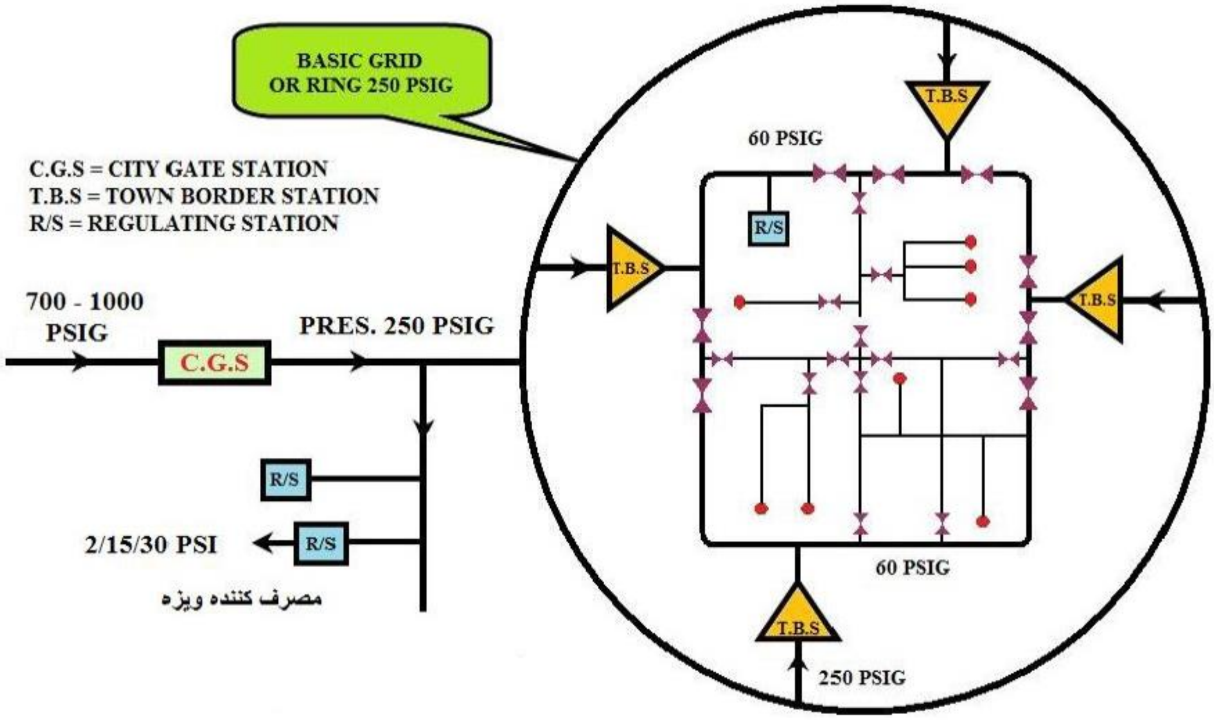

Figure 1: Schematic of the gas distribution system

Due to the sensitivity of urban gas pipelines in the gas supply process, it is necessary to identify all risks and analyze their applicability in order to prevent possible accidents and damages, and based on that, the existing risks are identified and properly managed, hence many researches have been done in this field. In (Rezaeisabzevar et al., 2020) carried out a quantitative risk assessment in gas distribution networks. Their method includes three parts; it was system description, risk detection and estimation and prediction of failures and their consequences (Jena et al., 2021). Many studies have been conducted regarding the investigation of external or third-party factors in the vicinity of gas pipelines, the most important of which can be mentioned is the study of (Abdolkhaninezhad et al., 202) it has been introduced around the pipeline. In (Idris et al., 2022) conducted a research work on risk assessment in the gas distribution network. Their focus in that research work, like the work of (Balogun et al., 2022), was on the consequences of accidents such as explosions and fires. In (Mrówczyńska et al., 2022) gave, they combined the methods of relative risk score and fuzzy logic system in a new method. The results of this research showed that the mentioned model provides accurate output and can be used as an intelligent risk assessment tool. In (Ayyildiz, 2022) conducted a risk assessment for an oil pipeline using the indexing method. In that research, population changes and spatial changes along the pipeline were not investigated and only numerical scoring was limited. In (Zarandiet al., 2021), by presenting a hybrid model based on the integration of the indexing system and the hierarchical analysis method, they assessed the risk of the gas pipeline. In a research work (Liu et al., 2019), examined 20 influential factors in increasing the risk of fire caused by the city gas network, especially during an earthquake. In their research, by combining the decision-making method and GIS methods, while determining the importance of the effective criteria, he prepared a micro-zoning map of the risk of fire caused by the gas network. The special importance of his work is that he dealt with many influential factors as a third factor (Ortiz-Barrios, 2020).

In (Ortiz-Barrios, 2020) investigated the incidents and consequences of gas pipeline failures, especially explosions. In (Gaur et al., 2022) with a new method based on cloud inference, analyzed the risks of gas pipelines. They considered factors such as injuries caused by unnatural factors, design flaws, biological erosion, and factors related to equipment life, etc. in their model. They used natural and virtual cloud converters for their evaluation (Sari et al. 2020). There have been researches related to the risk and risk management of gas pipelines in a research conducted by (Kalifa., 2022) using the genetic algorithm method to evaluate the risks of gas pipelines. In (Zambrano-Asanza, 2022) assessed the risk of oil and gas pipelines based on the fuzzy Bow-tie method. Using this method, which is a semi-quantitative qualitative method, they found that third-party factors, initial defects in pipeline materials and construction, it has the highest importance in the destruction of gas and oil pipelines. In (Zhou et al., 2016) assessed the risk of urban gas distribution network using hierarchical analysis. In the risk assessment process carried out in this study, due to the lack of complete access to information as well as the weighting criteria, the technique was used to manage the risk of urban gas distribution network. By examining the statistics of leakage events in the gas distribution network, the effective factors of hierarchical analysis were identified and the weight of each was determined by the process of hierarchical analysis. By reviewing the works done, it is clear that there have been many studies on the risk analysis of urban gas networks and each of them has pointed to parts of the pipelines. But until now, the factors affecting the risk assessment of city gas network lines using multi-criteria decision making method and the use of hierarchical AHP method is a research gap that has not been paid much attention to and has been addressed in the present study.

In general, the goals of this research are: 1- Identifying failure modes of urban gas pipelines 2- Risk calculation and assessment of urban gas pipeline failure modes 3- Risk control and management in urban gas pipelines in order to improve the level of safety in them 4- Choosing the best option based on various criteria for safety in urban gas pipelines. Due to its flammability and explosion, natural gas can be the cause of major accidents, therefore, knowing the risks caused by it will be an important factor in reducing the related financial and life losses. The gas company must have full knowledge of these hazards, risks and their control. Conducting this research can be an effective step towards a more accurate understanding of risk-forming factors and evaluation of the effectiveness of existing controls, and ultimately help to increase the safety level of gas pipelines. In short, the difference of this research compared to other researches in this field can be summarized as follows: 1. Different types of failure modes of urban gas pipelines were investigated. 2. Various dimensions of possibilities, consequences and risk levels related to failure modes of urban gas pipelines were investigated. This multifaceted view makes decision makers pay attention to different dimensions and increase their scope of vision. 3. Scientific solutions and suggestions were presented to reduce the risks of gas pipelines.

2 Methodology

Risk management is a dynamic process and indicates the identification, evaluation and economic control of all types of risks. In order to establish a written system of risk management in the organization, it is first necessary to determine the scope and extent of the risk and to study it in order to collect relevant information. The better the quality of information? The results of risk management will be more consistent with reality. In the next step, risks will be identified and risk qualitative analysis will be reviewed. At this stage, which is known as risk analysis, all obvious and hidden risks are identified and the value of each risk is determined qualitatively. Then, analysis of probabilities and modeling of the consequences of accidents is done in order to determine the severity of risks. This stage is known as quantitative risk analysis. The sum of qualitative and quantitative risk analysis steps is called risk assessment (Mrówczyńska et al. 2022). Figure 2 shows the stages of the risk management process. Finally, if the amount of risk under consideration is acceptable, the operation will be over. However, in case of non-acceptance, appropriate corrective measures should be taken to control the risk, moreover, the mentioned route should be repeated and reviewed at specific times. (Ayyildiz, 2022) By examining the statistics of risks that occurred in the gas distribution network, the effective factors were identified and the weight of each was determined by the Analytical Hierarchy Process (AHP).

Figure 2: Risk management process steps (Ayyildiz, 2022)

The structure of the risk acceptance criteria is organized in three parts as shown in Figure 3. This form is known as risk carrot. The upper part shows the unacceptable risk area and the lower part shows the risk area that can be ignored. The area between the upper part and the lower part is the place where the amount of personal, occupational and social risk should be reduced as much as possible (Ayyildiz, 2022). In order to estimate the quality of risk, the probability diagram and the control known as "Risk Matrix" are used. According to figure (4), intensity is shown on the horizontal axis and probability on the vertical axis. Parameters or numbers are attributed to probability and qualitative intensity and indicate their ascending and descending order. The arrays in the matrix are qualitative and show the risk value, and the order of the matrix depends on the number of definitions of probability and severity. For example, Figure 4 corresponds to a 4x4 matrix. It should be noted that the order of the matrix is directly related to its accuracy. In the case of several risk matrices, the maximum risk value is finally reported (Ayyildiz, 2022).

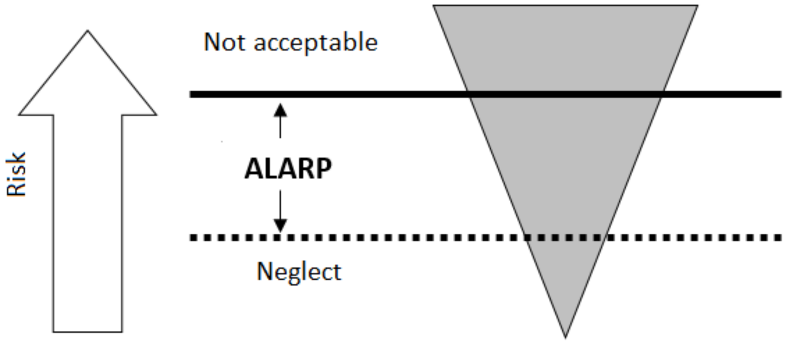

Figure 3: Risk Analysis

Increase the probability

D	Low	Medium	High	High
C	Very Low	Low	Medium	High
B	Very Low	Very Low	Low	Medium
A	Very Low	Very Low	Very Low	Low
	A	B	C	D

increase in intensity

Figure 4: Risk intensity

The risk matrix does not necessarily have to be symmetrical. According to Tiller, asymmetric risk matrix can also be defined. It is common to use colors instead of numbers and letters for the arrays inside the matrix. Figure 5 shows an example of an asymmetric matrix (Ayyildiz, 2022).

Probability					**Risk Matrix**	
5	**4**	**3**	**2**	**1**		
					Low	**Intense**
					High	
					Very high	
Low risk		Medium risk		High risk		

Figure 5: Risk Matrix

2.1 Multiple Criteria Decision Making

The word "decision" means "to decide" and its general meaning is to determine the intention and to reach a conclusion and resolve. Decision-making is defined as choosing one solution from among several solutions. Until now, various theories and methods have been presented for decision-making in researchers' problems, but since the era of the industrial movement in the world and especially since the Second World War, optimization models have been the focus of many mathematicians and industry practitioners. The main emphasis on classical optimization models is to have a criterion (or an objective function), so that the said model can be linear, non-linear, or mixed, but the attention of researchers in recent decades has been focused on multi-criteria models. It is used to measure complex decisions. MCDM multi-criteria decision-making is a large set of operations research that helps managers to make decisions based on multiple and conflicting criteria. If in multi-criteria decision making, the criterion is an index, it is known as MADM multi-criteria decision making. If the meaning of multiple criteria is the goal, it is called decision-making with multiple goals (MODM). In organizational issues where managers deal with criteria that have different scales for measurement and sometimes conflict with each other, it is very appropriate to use these methods. The use of multi-criteria decision-making methods in solving organizational problems is compatible with the complex nature of organizations. Decision making is one of the most important and fundamental tasks of management and the realization of organizational goals depends on its quality (Balogun, 2022).

2.2 Calculation of incompatibility index

$\lambda \max$ is always greater than or equal to n, and if the matrix deviates from the compatibility state, it will deviate from n. Therefore, the difference $\lambda \max$ and n can be a good criterion to measure the incompatibility of the matrix (Zarandi et al., 2021). $\lambda \max$ is the criterion weight of the row of the valuation matrix * column of the weights

$$I.I = \frac{\sum \lambda \max - n}{n-1}$$

2.6.6 Calculation of random matrix inconsistency index

They have calculated the values of the inconsistency index for the matrices whose numbers have been chosen completely randomly and called it the random matrix inconsistency index.
Calculation of incompatibility rate: For each matrix, the result of dividing the inconsistency index by the inconsistency index of the random matrix is then a suitable criterion for judging the inconsistency, which we call the inconsistency rate: $\mathrm{IR} = \frac{\mathrm{I.I}}{\mathrm{I.I.R}}$

The acceptable level of inconsistency of a matrix or system depends on the decision maker, but (Sari et al., 2020) presents 0.1 as an acceptable limit and believes that if the inconsistency is more than 0.1, it is better to revise the judgments.

3. Results

Today, gas pipelines are one of the centers of accidents, so that their accidents can have various consequences in different human, social, financial, political or environmental dimensions. For this reason, risk management and assessment is one of the most important activities for gas pipeline networks, especially in cities.

3.1 Analysis of failure modes

Due to the fact that during different periods, no process regarding the failure modes of city gas pipelines in region 2 had been done, therefore, in the first step, all the documents related to the failures were extracted and collected from the repair and relief units. All causes of failures related to pipelines and gas pipelines were categorized according to Table 1.

Table 1: List of gas failure modes

No	Cause of failure	No	Cause of failure
1	Collision of car and other vehicles with gas	**7**	Leakage from network connections (no standard welding)
2	Drilling organizations	**8**	Leakage due to landslides
3	Excavating real persons	**9**	Lack of standard welding
4	Debris fall (due to flood/worn structure of the building and other incidents)	**10**	landslide
5	Failure of valves (lack of standard lubrication)	**11**	Damage to pipe insulation and pipe rot
6	Leakage from Riser pipe joints (collision and breakage)	**12**	Pipe leakage (rotting and corrosion)

Due to the fact that the failures that occurred on the city gas pipelines mainly occur on the gas network and cylinder gas, for this purpose, in the second step, the causes of failure mentioned in table 455 were divided into the following four categories based on the type of failure: 1- Network failure 2- Leakage of Riser pipe connections 3- Leakage of network and connections 4- gas depth fracture. Natural gas passes through different gas supply networks to reach consumers. Natural gas reaches the gate of the city through the main lines that make up the transmission network, then it is transferred to the consumers that include domestic, industrial and special consumers using the distribution network. Therefore, maintaining the safety of gas pipelines is of particular importance. According to the extracted data and information, the main breakdowns on the network during the 5-year period in the gas administration of region 2 related to the unauthorized drilling of natural persons as well as the drilling of various organizations, which were mostly without inquiry from the gas company. It is given in figures 6, 7.

Figure 6: Excavator collision with gas steel grid

Figure 7: Excavator collision with polyethylene gas grid

In Table 2, the breakdown of the gas network in the last 5 years is shown separately.

Table 2: The causes of the failure mode of the gas network in the last 5 years

Total	2022	2021	2020	2019	2018	Year
35	12	7	7	5	4	Drilling organizations
8	3	2	1	1	1	Excavating real persons
43	**15**	**9**	**8**	**6**	**5**	Sum of cases

Since attracting the opinions of experts and group decision-making is one of the most important measures that increases the credibility of decisions, at different stages, the opinions of officials and experts involved in the maintenance and repair of pipelines of the gas company have been given serious attention.

Table 3: Risk assessment of the failure modes of Gas Company

Failure mode	Causes of failure	Number of each failure	Number of each failure	The probability of any of the causes of failure	Probability of failure mode	consequences	* The amount of consequence caused by the occurrence of each cause of failure	**Risk**
Network failure	Drilling organizations	35	43	0/81	0/03	Gas cut/reduction of network security/damage to gas facilities/environmental pollution/social dissatisfaction	56.000.000	1.680.000
	Excavating persons	8		0/19			42.000.000	1.260.000
Gas cylinder fracture	Car collision	246	347	0/71	0/28	Gas cut/damage to gas facilities/environmental pollution/social dissatisfaction	25.000.000	7.000.000
	Drilling organizations	48		0/14			30.000.000	8.400.000
	Excavating persons	35		0/10			25.000.000	7.000.000
	Debris fall, flood and...	18		0/05			25.000.000	7.000.000
network leakage and connections	Malfunction of network valves	520	655	0/80	0/53	Gas cut/reduction of network security/damage to gas facilities/environmental pollution/social dissatisfaction	28.000.000	14.840.000
	Leakage from joints due to impact	49		0/07			14.000.000	7.420.000
	Leakage from joints due to landslides	14		0/02			65.000.000	34.450.000
	Leakage from joints due to non-standard welding	72		0/11			15.000.000	7.950.000
Leakage of Riser pipe connections	Leakage due to non-standard welding	31	197	0/16	0/16	Gas cut/reduction of network security/damage to gas facilities/environmental pollution/social dissatisfaction	5.000.000	800.000
	Leakage due to landslides	12		0/06			25.000.000	4.000.000
	Leakage due to damage to pipe insulation and decay	154		0/78			4.000.000	640.000

3.2 Multi-criteria decision-making based on risk

Based on the risk assessment carried out in the previous stage, the two failure cases of gas valve breakage and network and connection leakage were selected as the most critical modes of failure based on risk, and the suggestions related to improving the condition of these modes, which were made after consultation with officials and experts in the field of operation and the selected gas network repairs are given in Table 4.

Table 4: Suggestions for improving the gas network

	Offers	Causes of failure
A	Inquiry from the gas company before any drilling operation	Gas cylinder fracture
B	Installation of a shock absorber on the sheath of the blades	
C	Increasing the thickness of the sheath of the cylinder	
D	Implementation of insulation up to the end of the pipe	network leakage and connections
E	Periodic repairs to remove the rotting of the cylinder	
F	Training of valve and repair personnel	
G	Obligation of welders to provide a certificate confirming the qualification of welding on an annual basis	
H	Cultivation and advertising	
I	Choosing the right type and size of the pipe when designing the lines to prevent pressure on the pipe and its erosion	
J	Coordinating with the municipality to move the gas facilities on the buildings and widening the alleys	

Table 5 summarizes the relative weight of options based on four main criteria, which are named N, M, Y and X according to Table 5 to facilitate the calculation.

Table 5: relative weight of options

	Cases / Criteria	**Possibility N**	**The rate of reduction of the outcome M**	**The amount of reduction in the probability of occurrence Y**	**The cost of implementation X**
A	Inquiry from the gas company before any drilling operation	2.105	2.493	2.784	2.634
B	Installation of a shock absorber on the sheath of the blades	0.382	1.858	1.682	0.369
C	Increasing the thickness of the sheath of the cylinder	0.330	1.230	1.348	0.281
D	Implementation of insulation up to the end of the pipe	0.373	1.228	0.992	0.518
E	Periodic repairs to remove the rotting of the cylinder	0.665	1.028	1.269	0.531
F	Training of valve personnel	2.334	0.799	0.419	1.997
G	Requiring welders to submit a certificate confirming the qualification of welders on an annual basis	1.125	0.411	0.309	0.797
H	Cultivation and advertising	0.485	0.189	0.499	0.533
I	Choosing the right type and size of pipe when designing the lines	0.905	0.274	0.323	1.147
J	Coordinating with the municipality to move the gas facilities on the buildings and widening the alleys	1.295	0.491	0.376	1.192

According to tables 3-24 and 3-25, the final weight of options is calculated as follows:

A: (Z1 * N1) + (Z2 * M1) + (Z3 * Y1) + (Z4 * X1): 0691
B: (Z1 * N2) + (Z2 * M2) + (Z3 * Y2) + (Z4 * X2): 2.341
C: (Z1 * N3) + (Z2 * M3) + (Z3 * Y3) + (Z4 * X3): 0.945
D: (Z1 * N4) + (Z2 * M4) + (Z3 * Y4) + (Z4 * X4): 0.797
E: (Z1 * N5) + (Z2 * M5) + (Z3 * Y5) + (Z4 * X5): 0.676
F: (Z1 * N6) + (Z2 * M6) + (Z3 * Y6) + (Z4 * X6): 1.673
G: (Z1 * N7) + (Z2 * M7) + (Z3 * Y7) + (Z4 * X7): 0.945
H: (Z1 * N8) + (Z2 * M8) + (Z3 * Y8) + (Z4 * X8): 0.831
I: (Z1 * N9) + (Z2 * M9) + (Z3 * Y9) + (Z4 * X9): 0.412
J: (Z1 * N10) + (Z2 * M10) + (Z3 * Y10) + (Z4 * X10): 0.911

4 Conclusion

Our study in this research was to assess the risk of urban gas pipelines, we did the necessary investigations in this regard and the works that were done are as follows:

- Extraction of all the causes of failures in the gas lines based on the data of the last 5 years
- Separation of the extracted failure causes into four parts (four failure modes)
- Calculate the probability of each failure cause
- Calculation of probability of occurrence of failure modes - Classification of consequences related to each failure mode
- Calculation of the amount of consequences caused by the occurrence of each of the causes of failure
- Assessment of the risk of failure modes in the last 5 years

And after assessing the risk of failure modes, we were able to select 2 failure cases as the most critical failure modes among the examined failure modes. In the next step, we put forward some suggestions from the point of view of risk to improve the gas supply of region 2, and to prioritize the suggestions, we used the multi-criteria decision-making method and the AHP hierarchical model, and after identifying the criteria for evaluating the improvement of the gas supply, using the method AHP for the four criteria of reducing the cost of implementation, reducing the consequences, reducing the probability of occurrence and feasibility. In the first step, according to the AHP method, we formed a decision tree which consisted of three levels of objectives, criteria and indicators, and in the second step, paired comparisons were made for four we did the main criteria two by two and we were able to determine the preference of the criteria. Finally, according to the Risk Matrix method, in order to obtain the relative weight of the criteria, we normalized and found the line average of each criterion, and in this way, we were able to obtain the relative weight of the main criteria. One of the suggestions made in this research has been implemented and monitored and evaluated by experts. - Other decision-making methods should be used for evaluation. It is suggested to use and evaluate this method for other regions of the gas company as well. The MODM method should be used to evaluate indicators and criteria and optimization should be done based on the definition of the objective function and constraints.

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