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A Risk and Reliability-Based Scheduling Method for Troubleshooting Regulators in Gas Pressure Stations: A Case Study of Isfahan Gas Company

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ABSTRACT

Objective: This research presents a new method for scheduling troubleshooting operations of station regulators in natural gas distribution stations, focusing on the importance index of equipment, reliability, and risk management.

Methods: Using reliability-based maintenance principles and the expertise of professionals from Isfahan Gas Company, we selected 166 regulators from 112 pressure reduction stations in Isfahan. We assessed the importance index of each station and evaluated the potential consequences of its failure risks, followed by calculating its reliability metrics. The results were grouped using the K-means clustering method. Ultimately, we identified the optimal time frame for conducting troubleshooting operations.

Results: In this study, 166 regulators were grouped into three clusters. The average time required to perform troubleshooting activities varied among the clusters. For the first cluster, the average time was determined to be 48 hours. The second cluster had an average troubleshooting time of 544 hours, while the third cluster had an average of 829 hours. Currently, the average time for troubleshooting regulators is 720 hours.

Conclusion: This paper presents the following contributions: 1. Identification of the station importance index based on the gas supply mission to subscribers and end consumers. 2. Localization of the method for estimating risks and consequences arising from station equipment failures. 3. Assessment of equipment reliability. 4. Clustering of key regulatory equipment in the case study.

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Introduction

With the increasing number of complex equipment and the changing attitude of organizations towards maintenance responsibilities, new maintenance techniques have become vital. Maintenance management is a set of technical, executive, administrative, and managerial activities carried out throughout the life cycle of the equipment, and its goal is to put the device in a ready-to-use state to provide the expected performance (Pilanawithana et al., 2022).

One of the most important activities related to maintenance is maintenance planning, which is a structured set of activities, work procedures, resources, and appropriate time scales for carrying out maintenance activities. When the plan is prepared, all the activities required for maintenance are identified. The development of preventive maintenance plans is based on the recommendations and instructions of manufacturers, experiences in using similar equipment, studying the technical documentation of the equipment, maintenance engineering methods, and management requirements. However, in cases where the recommendations of the equipment manufacturers are not precisely specified, or the equipment has a high financial value or is classified as critical equipment, structured analyses such as RCM (Reliability Centered Maintenance) should be used. Reliability-based maintenance may be considered the most powerful tool in defining maintenance activities, determining their intervals, and implementing them (Ge et al., 2024).

With the development of natural gas supply and distribution projects as one of the primary energy distribution arteries in the country, the maintenance and protection of gas supply facilities and infrastructures, as a significant part of the physical assets of the gas company, is of particular importance (Shahin et al., 2013). Proper management of this equipment requires a documented and continuous program that can be used to plan and implement appropriate techniques in the field of maintenance management. The facilities and structures used in the natural gas supply and distribution industry include pressure reduction stations and cathodic protection stations, feed lines and distribution networks, valves, regulators, and meters. Currently, different maintenance approaches are considered for each equipment group depending on the manufacturers' recommendations and past repair records. In this way, some of the equipment has operational service until a failure occurs. Another part has preventive maintenance programs in the Isfahan Gas Company at predetermined periods. With the development of gas supply projects, and considering that more than fifty years have passed since the establishment of Isfahan Gas Company, the age of gas supply facilities and equipment causes wear and tear and sudden failures (Shahin et al., 2013). For this reason, and to prevent any fluctuations in the supply of gas required by subscribers, especially in the cold seasons of the year, and in order to prevent accidents caused by improper equipment performance, it is necessary to use the mechanisms recommended by experts and reputable scientific authorities in the field of maintenance, repairs and reliability to enhance the useful life of equipment and improve their performance.

In the present study, the importance index of the pressure reduction stations of Isfahan Gas Company in the studied city is determined by dividing them into three groups: critical, semi-critical, and non-critical equipment. Then, using the importance, reliability, and risk indices, a new method is proposed to determine the appropriate maintenance period for one of the key gas supply equipment in each group of pressure reduction stations. The following will introduce the research background on maintenance and risk management. In the methodology section, pressure reduction stations will be clustered using the K-means method and the importance, reliability, and risk indices. The clustering results will be examined and analyzed. Finally, suggestions for future research will be made based on the results obtained.

Literature Background

Maintenance

Maintenance goals can be divided into technical, legal, regulatory, and financial goals with risk reduction. The ability of an organization to achieve an effective maintenance strategy indicates the ability of that organization to predict production needs and requirements, which will reduce non-separable maintenance costs, such as reducing production waste, preventing service interruptions, avoiding stakeholder dissatisfaction, etc. (Olutimehin et al., 2025).

Currently, in many industries, the intervals between preventive maintenance activities are determined based on the expertise and experience of technical personnel or the device manufacturer's recommendations in its manual. Determining an optimal interval with the help of scientific methods for performing preventive maintenance activities significantly affects an industry in terms of reducing costs, increasing equipment reliability, reducing equipment downtime, etc. Reliability-based maintenance is a process that determines what activities must be performed to ensure that the equipment will perform its tasks correctly and with minimal risk. In fact, RCM is a guide to identifying maintenance activities and their implementation frequency (Geisbush & Ariaratnam, 2023). The advantages of using the reliability-based maintenance method include rapid detection of failures, eliminating the cause of some failures before they occur, and eliminating the root cause of some failures by changing the design. RCM is designed as a systematic method for determining optimal asset maintenance strategies. This approach first identifies the assets' key functions, evaluates potential failure modes, and prioritizes maintenance tasks (Preußker et al., 2024). This process helps organizations accurately determine maintenance times and prevent unexpected failures. As a result, this approach can lead to reduced maintenance costs, increased mechanical availability, and reduced equipment downtime (Song et al., 2023).

Risk Management

Risk management is a systematic process for identifying, assessing, and managing operational risks that can impact the achievement of organizational goals (ISO[1] 31010). According to this standard, the risk management process includes five stages: communication and consultation, establishing the context, risk assessment, risk control, and monitoring and review. The FMEA[2] method identifies potential failure modes in system components, determines causes, evaluates their effects on system performance, and determines ways to reduce the chance of occurrence and consequences and increase the ability to detect failure modes. This method is known as the most important operational tool for performing RCM, and, due to its practical and qualitative approach in the industry, it is the most widely accepted method for risk and reliability analysis. For a specific process, FMEA identifies failure modes, states the cause of failures and their intervals (reliability), and also the effects that each failure will have on the overall process, or in other words, determines the risk (Siahaan et al., 2024). In the FMEA method, the Risk Priority Number (RPN) index is used to calculate the risk of a system failure mode, which is the product of three numbers: probability of occurrence, severity of consequence, and detectability. The higher the RPN value, the greater the risk associated with the failure mode in question (Kumar et al., 2024). Predictive maintenance and risk management in various industries, especially petrochemical, automotive, and nuclear energy, are expanding widely. Research conducted in the oil and gas industry shows that risk management, especially in conditions of market uncertainty, can effectively help reduce costs and improve system efficiency (Attia, 2025). In this regard, scenario simulation to predict failures and maintenance needs in industrial processes improves management decision-making.

Maintenance and Risk Management

The relationship between reliability-based maintenance (RCM) and risk management is one of the most important topics in various industries, and it helps to optimize equipment performance, reduce costs, and increase safety and productivity. This area is critical in heavy industries such as oil and gas, aerospace, and maritime. Over the past few decades, various methods have been proposed to integrate these two areas, which can reduce failures, improve uptime, and increase safety. Research shows that using RCM and its combination with risk management can help improve system

[1] ISO 31010 (Risk Management Techniques)
[2] Failure Modes and Effects Analysis

efficiency and reduce maintenance costs. In this regard, the reliability-based maintenance (RRCM) approach, by combining these two approaches, improves maintenance planning while paying attention to reliability, risk, and costs (Gandhare et al., 2025).

A study by Olutimehin et al. (2025) has shown that combining AI and IoT with predictive maintenance systems can significantly improve system performance and minimize risks. This research focuses on advanced simulations and real-time data analysis to predict failures and shows that this approach can help identify problems early and reduce maintenance costs. At the same time, Attia (2025) emphasized that using risk management and integrated maintenance planning in conditions of market uncertainty can lead to cost reduction and improved system performance in the oil and gas industry. This study particularly emphasizes the importance of scenario simulation and the more accurate prediction of failures in the oil and gas industry. In contrast, Wang et al. (2024) focused on multi-factor simulations to analyze ship maintenance risks. This research shows that using multi-factor simulations for risk assessment can help identify systematic and unsystematic failures and thus take preventive measures promptly. This research emphasizes explicitly the analysis of risks in complex environments. In this regard, Kıvanç et al. (2025) have shown in the aerospace industry that using safety and risk management systems in aircraft maintenance can reduce accidents caused by failures and improve safety. This research emphasizes the need for human resource training and advanced technologies to predict failures and reduce risks.

Fan et al. (2024) investigated the use of predictive algorithms for risk management in solar energy systems. This research showed that predicting failures and using predictive models can help reduce operational risks and maintenance costs in the energy industry. Also, in another study conducted by Goni et al. (2024) in the petrochemical industry, proactive risk management and its combination with predictive maintenance processes have helped reduce failures and improve system performance. This study emphasizes that implementing predictive and analytical systems can effectively prevent unexpected failures and reduce maintenance costs, as shown in the study by Soltani et al. (2020) in the automotive industry, predictive maintenance-based risk management was examined. This study showed that accurate failure prediction using data-driven models can improve equipment performance and reduce costs related to emergency repairs.

Paltrinieri (2017) examined risk management in maintenance projects based on real-time data. The results showed that real-time data and its analysis can help reduce the risks associated with failures and more accurately predict problems. Further, Xu et al. (2018) examined risk management in smart maintenance operations and showed that real-time data and predictive algorithms can prevent unexpected failures and keep systems in an optimal state. Also, Jasiulewicz-Kaczmarek et al. (2020) analyzed the impact of advanced technologies in reducing the risks of maintenance operations and concluded that modern technologies can help reduce maintenance costs and improve equipment performance.

Combining RCM and RPN is a practical approach to identifying and evaluating system failures and prioritizing them. While RCM provides a structured framework for analyzing failures and selecting maintenance strategies, RPN, as a quantitative assessment tool, helps managers make informed decisions about which failures require immediate attention. An important point in the relationship between RPN and RCM is that RPN is used directly in the FMEA phase, an important part of RCM, to determine the significance of failures. In fact, after calculating the RPN for each failure mode, it can be identified which failures require immediate planning.

In various papers, combining RCM and RPN is a powerful tool for optimizing maintenance strategies and increasing system performance. For example, Gupta et al. (2016), in their review of RCM for a typical lathe machine, showed that using RPN can help prioritize failure modes. The paper emphasizes that RCM can be used to select the appropriate maintenance strategy after calculating the RPN for each failure mode. In particular, RCM helps managers to know which parts of the system need preventive maintenance to minimize failures. The paper by Sulistiyono et al. (2008) showed that RPN is used in FMEA analyses to identify different risks of systems (especially in high-pressure boilers). The paper points out that using RCM II and RPN, more accurate schedules for preventive maintenance can be specified, and possible failures can be avoided. In another study, Rodriguez et al. (2023) used K-Means clustering to analyze maintenance data and concluded that this method can help improve efficiency and reduce maintenance costs. In previous research, RCM has been used as a comprehensive approach to manage maintenance strategies, and RPN has been used as a tool for prioritizing risks.

Literature background in the Gas Industry

Shan et al. (2024) presented a method for determining the maximum allowable repair time for critical and significant equipment in natural gas transmission facilities using the gas supply reliability theory. A study to optimize and select gas turbine generator maintenance policies based on hybrid reliability was conducted by Alrifaey et al. (2020), which resulted in a reduction in maintenance costs.

Mohtadi and Sheikh Rabiei (2021) evaluated the important factors in an optimal maintenance strategy and selected the desired strategy from the proposed strategies based on the aforementioned factors. Then, the level of equipment risk in the South Pars Refinery was considered using the interpretive structural equation modeling and the analytic hierarchy process. This method is designed based on the life cycle cost and availability framework, which is a function of the mean time to failure and the mean time to repair. The results of this study show that a combination of repair activities of replacing the pipe coating and replacing part of the transmission line over a life span of 30 to 40 years is the most effective maintenance activity in terms of cost and availability. Hokmabadi et al. (2022) identified 35 risks of pressure reduction station equipment using the FMEA method and prioritized them using a mixed decision-making method. The results of this study showed that oscilloscope regulator failure, safety valve failure, and regulator diaphragm rupture ranked first to third, respectively.

In their study, Khedari et al. (2020) presented an approach to evaluating maintenance performance based on unbreakable components in ten gas transmission operation areas in the country and, using the fuzzy Delphi method, identified sixteen indicators appropriate to the activities of the ten gas operation areas from the key indicators for evaluating maintenance performance derived from various global standards. In their research on the reliability-based maintenance methodology in the gas pressure reduction system, Salehian and Jahan (2022) shared the initial experiences of implementing the system in Semnan Province Gas Distribution Company, and by selecting the most critical equipment to implement the reliability-based maintenance methodology based on existing data records, by identifying functions, functional failures, failure modes, and effects, they determined the appropriate maintenance activity for each failure mode of the equipment in question.

In Isfahan Gas Company, the maintenance program based on the gas supply capacity of the pressure reduction stations is routinely carried out by maintenance teams at monthly intervals to test the performance of regulators related to high-capacity stations; an appropriate and documented maintenance program has not been considered for the equipment of the pressure reduction and measurement stations, and in most cases the equipment has been used to the point of failure. This planning has not considered important indicators such as the station importance index program and its failure risk.

This study considers the continuity of safe gas supply operations and ensuring the correct operation of regulators in pressure reduction stations. Therefore, the main goal of this study is to determine an appropriate schedule for testing the performance of regulators, appropriate to the installation location (pressure reduction station importance index), reliability indices, and risk from regulator failure. Therefore, this study tries to define an appropriate schedule for performing maintenance operations by utilizing the concept of reliability and risk management, having records and data on regulator equipment failure, and using a reliability-based maintenance method for each of the regulators used in pressure reduction stations.

Knowledge Gap and Research Innovation

In many previous studies, maintenance operations have been planned more generally and without considering specific indicators for pressure reduction stations. Often, no comprehensive and indigenous approach has been available to determine the timing and prioritization of troubleshooting operations using specific parameters such as station importance index, reliability, and risk assessment.

Also, many previous studies in this field have either been conducted based on limited and imprecise data or their results have been tested in other industrial environments that may not be generalizable to the gas industry. Especially in the case of pressure reduction stations and their related equipment, no accurate and consistent data have been available for risk analysis and determining the timing of maintenance operations in Iran.

On the other hand, in previous studies, the timing of maintenance operations has been determined only based on the experience or recommendations of equipment manufacturers, which sometimes leads to inefficient schedules and increased maintenance costs. In particular, the lack of more advanced models, such as K-means clustering and risk assessment, in strategic decision-making has led to the failure to achieve optimal results.

Therefore, the present study has several innovative aspects:

1) Combining the device importance index with RPN and RCM in maintenance planning: One of the outstanding innovations of this study is introducing and combining the device importance index with two criteria, RPN and RCM. This combination makes decisions regarding the timing and prioritization of troubleshooting and repair operations more accurate and with higher precision. In other words, in this study, not only risk analysis (RPN) and reliability (RCM) are considered, but the importance of the device in pressure reduction stations is also considered as a key factor in better prioritizing maintenance plans.

2) Clustering and classification based on importance index, RPN, and RCM: This research has innovatively used the K-means algorithm to cluster and classify pressure-reducing stations and regulators based on importance index, RPN, and RCM. This classification method clearly divides regulators into critical, semi-critical, and non-critical groups and accordingly determines a more accurate timing for troubleshooting and repair operations. This clustering helps managers to allocate resources and efforts more effectively and efficiently.

3) Localization of international standards for specific gas industry conditions: The research has set up an operational model tailored to local needs by localizing international standards such as ISO 14224 and NORSOK Z008:2011 for specific conditions of the gas industry in Iran. This

localization allows the models and methods to operate more accurately, according to the specific characteristics of gas supply equipment and the needs of Isfahan Province Gas Company.

4) Risk and reliability assessment as key factors in maintenance planning: This research has, for the first time, conducted a more accurate assessment of failure risk and reliability in the maintenance of gas supply equipment and examined them simultaneously with the device importance index. This assessment helps create a more accurate and optimal maintenance schedule, which ultimately reduces failures, increases equipment life, and improves gas supply systems' efficiency.

Materials and Methods

In order to achieve a maintenance program for regulators used in pressure reducing stations based on the importance indicators of pressure reducing stations, reliability indicators, and risk from regulator failure, we need to calculate the mentioned indicators in this study. In this study, while examining data related to the maintenance of pressure-reducing stations in one of the cities of Isfahan province, determining the appropriate time period for carrying out maintenance activities for the important regulator equipment in these stations has been investigated. The statistical population of this study includes all regulators used (166, assuming they are in their normal life cycle) in 112 pressure-reducing stations of the gas department of that city. Also, in order to benefit from the operational experiences and technical knowledge of managers and experts in the field of maintenance of pressure reducing stations, seven people who had more than 15 years of experience in this field and were personally willing to cooperate in conducting this research were selected as the expert group of this study. The steps of this research will be as follows:

1. Extracting information and technical specifications of the studied pressure reduction stations to determine the stations' importance.

2. Categorizing the pressure reduction stations in terms of importance index into three groups: critical, semi-critical, and non-critical;

3. Calculating the mean time between regulator equipment failures (MTBF), failure rate (λ), and reliability index (RCM), based on available failure records and maintenance operations recorded for the stations;

4. Determining the risk of failure of regulators for each station and calculating the RPN score for each regulator using the FMEA method localized in Isfahan Province Gas Company, with the participation of a group of experts;

5. Applying the K-means method to cluster the regulators installed in the studied stations based on RCM and RPN scores;

6. Determining the appropriate period for maintenance activities to prevent failure using the reliability-based maintenance process.

Excel software and VBA were used to analyze the data and cluster and classify the data in this research.[1] Coding in the macro environment and the K-means algorithm were used. Figure 1 shows the process of conducting this research.

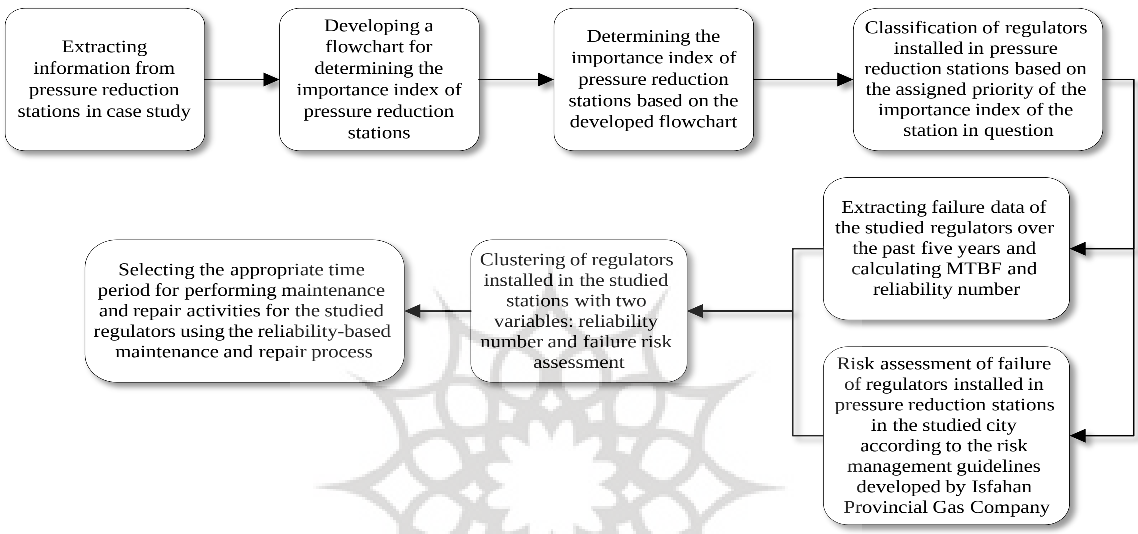

Figure 1. Overview of the research implementation stages in Isfahan Province Gas Company

Method for determining the importance index

Pressure reduction stations used in the natural gas distribution process are not in the same category in terms of importance, considering their installation location and end consumers. Therefore, to conduct this research, a working group of experts and experts in the field of maintenances was formed in Isfahan Province Gas Company and using international standards in this field such as the NORSOK Z008:2011 standard and the ISO14224:2016 standard, a standard method was developed to classify pressure reduction stations in Isfahan Province Gas Company into three groups of critical, semi-critical and non-critical stations. On this basis, pressure reduction stations were classified and defined in three categories:

1) Critical pressure reduction stations: Stations in this group are those in which any failure that causes an operational stoppage results in the gas supply of important subscribers being cut off.

2) Semi-critical pressure reduction stations: Stations in this group are those in which any failure that causes an operational stoppage would result in a less significant gas cut-off for subscribers.

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[1] Visual Basic for Applications

3) Non-critical pressure reduction stations: Stations in this group are those in which any failure that causes an operational stoppage would not result in a significant gas cut-off.

To determine the importance index of pressure reduction stations, the scope of gas supply of that station to final consumers (subscribers) is taken into account. Based on the instructions issued by the National Iranian Gas Company and considering the importance of subscribers, using the opinions of the expert group in this field at the Isfahan Provincial Gas Company, the flowchart in Figure 2 was designed and used to conduct this research. Table 1 has been prepared based on the presented flowchart.

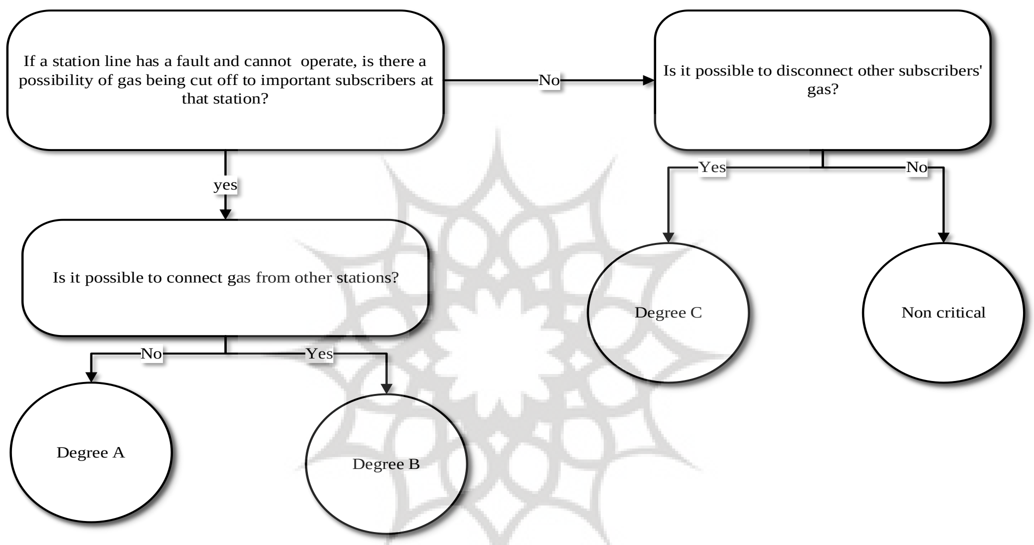

Figure 2. Flowchart for determining the station importance index from the gas supply operations to subscribers

Table 1. Determining the importance of pressure reduction stations based on gas supply operations to subscribers

Important subscribers	Degree A	Degree B	Degree C
Industrial Towns	Semi-critical	Non-Critical	Non-Critical
Industrial Zones	Semi-critical	Non-Critical	Non-Critical
Strategic industries with exclusive products	Critical	Semi-Critical	Non-Critical
Public service centers (bakeries, etc.)	Critical	Semi-Critical	Semi-Critical
Emergency centers (hospitals, fire departments, etc.)	Critical	Critical	Semi-Critical
Home subscribers	Critical	Critical	Semi-Critical
Power plants	Critical	Critical	Critical

Method of calculating the reliability index

The failure rate (λ) represents the number of failures per unit time and can be calculated by reversing the mean time between failures (MTBF). dt. λ (t) is the probability of failure of a device in the time interval t and t + dt. The failure function is represented by F (t), and the relationship between the probability of failure and the probability of failure is R (t) = 1-F (t). In the aforementioned relationship, R(t) is the probability that the device in question will go through a time t without failure and is called reliability. Assuming that the regulators are in their natural life cycle and the failure rate (λ) is constant over a period of time, the probability of the device not failing by time t (reliability number) is calculated from Equation 1 (Mohammad et al., 2022).

$R(t) = \exp(-\lambda * t)$ و $\lambda = 1/MTBF$ (1)

Risk Number Calculation Method

The Risk Number or RPN is calculated from the product of the occurrence, severity, and the detection coefficient in Equation 2 (Giesbusch & Ariratnam, 2022).

(RPN) Calculated Risk = O * S *D (2)

a) Occurrence (O): The chance of an event occurring, the time frequency of a hazard occurrence, which consists of three rare sets of records, recurrence, and probability. The scoring method for each of the three probability components is as follows. Score 1: Unlikely (once every 20 years); Score 2: Rarely (once every 10 years); Score 3: Possible (once every 5 years); Score 4: Probable (once every 2 years); Score 5: Frequent (once every year).

b) Severity (S): The impact of each failure mode is the consequence of that failure. These consequences include human, financial, and organizational reputational consequences, and the scoring for each component is calculated as follows. Score 1: Very minor consequence; Score 2: Minor consequence; Score 3: Moderate consequence; Score 4: Severe consequence; Score 5: Very severe consequence

c) Detection (D): This coefficient is defined as a measure of control capabilities used to determine the causes of failure and breakdown. In order to score the detectability parameter, it is scored as follows. Score 1: If the station is equipped with an online performance monitoring system. Score 3: If the station is equipped with an offline performance monitoring system. Score 5: If the station does not have a performance monitoring system.

K-means algorithm

K-means is a center-based or distance-based algorithm that calculates distances to assign a point to a cluster. In K-means, each cluster has a center. The main goal of the K-means algorithm is to minimize the sum of distances between points and the center of the corresponding cluster. In general, the steps of implementing the K-means algorithm are as follows (Brentan et al., 2018):

1. Determine the number of clusters (K)
2. Select K random numbers from the data as the coordinates of the cluster centers
3. Assign all points (data) to the nearest cluster center
4. Select the weighted average of the data of each cluster as its center
5. Repeat steps 3 and 4 until the stopping criterion is met.

Results

Based on the criteria provided by Isfahan Province Gas Company, after extracting station information, it was determined that out of the 112 stations in question, 50 stations were in a non-critical state, 36 were in a semi-critical state, and 26 were in a critical state. At this stage, by examining the repair records and failure data related to the regulators, in five years with 43,800 operating hours and a one-month monitoring period, the time intervals of failure in each of the regulators were extracted, and based on this, the average time index of the distance between two failures and the failure rate were calculated (in Table 2, these indices are calculated for the first ten regulators for example.) The operating hours over the past five years are 43,800 hours. Then, the risk of failure of each of the regulators under study in the pressure reduction stations of the studied city was assessed after holding technical expert meetings and benefiting from the expertise of the respected colleagues in the maintenance department of gas pressure reduction stations.

Table 2. Calculation of the reliability number of pressure reducing station regulators

Regulators' Number	Number of Defects	MTBF	λ	R(t)	Occurrence			Consequence			Detectability	RPN
					Records	Frequency	Probability	Life	Financial	Attitude		
1	10	4380	0.00023	0.8484	5	2	5	1	2	2	5	300
2	6	7300	0.00014	0.9061	5	2	5	1	2	2	5	300
3	11	3982	0.0025	0.8346	5	2	5	1	2	2	5	300
4	9	4867	0.00021	0.8625	5	2	5	1	4	4	5	540
5	6	7300	0.00014	0.9061	5	2	5	1	4	4	5	540
6	7	6257	0.00016	0.8913	5	2	5	1	4	4	3	324
7	10	4380	0.00023	0.8484	5	2	5	1	4	4	3	324
8	7	6257	0.00016	0.8913	4	1	5	1	5	4	5	500
9	9	4867	0.00021	0.8625	4	1	5	1	5	4	5	500
10	14	3129	0.00032	0.7944	4	1	5	1	5	4	5	500

Data clustering according to RCM and RPN

In order to perform data clustering based on the K-means algorithm, the number of desired clusters must first be selected. In this study, considering that pressure reduction stations are divided into three general categories: critical, semi-critical, and non-critical, the number of desired clusters is considered 3. After the final selection of the centers of each cluster and the assignment of reliability and risk assessment data points to the cluster associated with it, it can be assured that no change will be made in the clusters by repeating the data clustering when the objective function, i.e. the sum of Euclidean distances of all data points relative to the center of the cluster associated with it, is minimized. Therefore, in this study, the data clustering algorithm was repeated and executed many times, and the results of the objective function in 50 consecutive iterations are presented in the diagram below. As shown in the figure, in the 29th iteration, the objective function value is calculated at its minimum value and is selected as the final clustering solution. After 50 iterations of the K-means algorithm, in the 29th iteration, the objective function value is calculated at its minimum value and is selected as the final clustering solution. Table 3 shows the general information about each cluster.

Table 3. The characteristics of each cluster

Cluster ID	Number of regulators in a cluster	Regulators of stations with a critical importance index	Regulators of stations with a Semi-critical importance index	Regulators of stations with a non-critical importance index	RPN	RCM
Cluster1	67	53	12	2	599	0.8784
Cluster2	80	29	21	30	405	0.8875
Cluster3	19	3	16	0	137	0.8729
Total	166	85	49	32		0.8837

Scheduling of maintenance operations

Analysis of the first cluster: 67 regulators belonging to pressure reduction stations in Isfahan city are placed in the first cluster, of which 53 belong to pressure reduction stations with a critical importance index, 12 belong to pressure reduction stations with a semi-critical importance index, and two belong to regulators of pressure reduction stations with a non-critical importance index. The average risk assessment number of regulators in this cluster is 599, and the average reliability number calculated for regulators in this cluster is 0.8784. In order to determine the appropriate frequency for performing scheduled troubleshooting operations, using the standards established in this field and also applying the experiences of experts in this field in Isfahan Province Gas Company, the availability of regulators in this cluster was determined according to the corresponding pressure reduction station index, as shown in Table 4. Also, this table presents the frequency of troubleshooting activities in regulators belonging to cluster one.

Table 4. Availability of regulators and determination of the frequency of troubleshooting activities in the first cluster

	Critical stations	Semi-critical stations	Non-critical stations
availability of regulators based on the importance index of the desired pressure reduction station	99.9 %	99%	95%
Determining the frequency of troubleshooting activities as a percentage of MTBF	0.2%	2%	10%

In the second cluster, 80 regulators belonging to the pressure reduction stations of the city have been studied, of which 29 belong to pressure reduction stations with a critical importance index, 21 belong to pressure reduction stations with a semi-critical importance index, and 30 belong to pressure reduction station regulators with a non-critical importance index. The average risk assessment number of the regulators in this cluster is 405, and the average reliability number calculated for the regulators in this cluster is 0.8875. Table 5 shows the appropriate frequency periods for performing scheduled troubleshooting operations and the availability of the regulators in this cluster according to the corresponding pressure reduction station index.

Table 5. Availability of regulators based on the importance index of the desired pressure reduction station

	Critical stations	Semi-critical stations	Non-critical stations
availability of regulators based on the importance index of the desired pressure reduction station	99.9 %	95%	95%
Determining the frequency of troubleshooting activities as a percentage of MTBF	0.2%	10%	10%

In this cluster, 19 regulators belonging to the pressure reduction stations of the city have been studied, of which three belong to pressure reduction stations with a critical importance index, and 16 belong to pressure reduction stations with a semi-critical importance index. The average risk assessment number of the regulators in this cluster is 134, and the average reliability number calculated for the regulators in this cluster is 0.8862. Table 6 shows the appropriate frequency period for performing troubleshooting operations and the availability of the regulators in this cluster according to the corresponding pressure reduction station index.

Table 6. Availability of regulators based on the importance index of the desired pressure reduction station

	Critical stations	Semi-critical stations	Non-critical stations
availability of regulators based on the importance index of the desired pressure reduction station	95 %	95%	Not in this cluster
Determining the frequency of troubleshooting activities as a percentage of MTBF	10%	10%	Not in this cluster

Discussion

For sensitivity analysis and model validation, after the final selection of the centers of each cluster and the assignment of reliability and risk assessment data points to the cluster associated with it, it can be assured that no change will occur in the clusters by repeating the data clustering when the objective function, i.e. the sum of Euclidean distances of all data points to the center of the cluster associated with it, is minimized. Therefore, in this study, the module related to data clustering was repeated and executed many times, and the results of repeating this module and calculating the objective function in 50 consecutive iterations are presented in Figure 3.

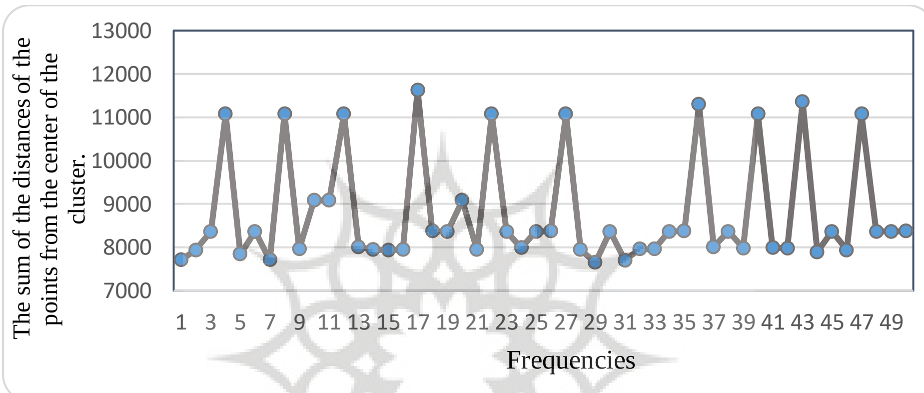

Figure 3. Graph of changes in the sum of Euclidean distances of research data from the center of the clusters

As shown in Figure 3, after 50 iterations of the K-Mean algorithm, in the twenty-ninth iteration, the value of the objective function is calculated at its lowest value, i.e., the number 7647. It is selected as the final clustering solution. In this case, the optimal coordinates of the centers of the three clusters are given in Table 7.

Table 7. Final coordinates of the centers of the triple clusters

Criteria	Cluster1	Cluster2	Cluster3
RPN	599	405	134
RCM	0.87840	0.8875	0.8862

Based on the existing implementation methods and instructions at the National Iranian Gas Company, the performance testing of precision instrumentation equipment of pressure reduction stations, including shut-off valves, safety valves, and regulators, is currently carried out monthly. In this regard, there is no difference between the importance index of pressure reduction stations, risks associated with equipment failure, and records and data of failures, and this will reduce the availability of equipment in pressure reduction stations and unwanted stops in gas supply operations, especially in the cold seasons of the year. With the method presented in this study, the time intervals for performing equipment troubleshooting activities were calculated more accurately in order to prevent unwanted failures. Based on the results of this study, the average time for performing troubleshooting activities in regulators belonging to the first cluster is determined to be 2 days, equivalent to 48 hours, while this period is currently 30 calendar days, equivalent to 720 hours. In the second cluster, the average time for troubleshooting activities in regulators is determined to be 23 days, equivalent to 544 hours, while this period is currently 30 calendar days, equivalent to 720 hours. In the last cluster, the average time for troubleshooting activities in regulators belonging to the third cluster is 34 days, equivalent to 829 hours, while this period is currently 30 calendar days, equivalent to 720 hours. In Table 8, changes in the frequency of troubleshooting operations and performance testing of the studied regulators are presented by station importance index after the research, compared to before.

Table 8. New frequency of troubleshooting activities by the regulators in this case study

Clusters	New period (hour)				Previous period (hour)
	Critical	Semi-critical	Non-critical	Cluster average	
Cluster1	16	127	639	54	720
Cluster2	156	748	776	544	720
Cluster3	1703	665	0	829	720
Average	163	693	767	436	720

Conclusion

In this study, the frequency of preventive troubleshooting and testing of the regulator performance as one of the most key equipment installed in the pressure reduction stations of the Isfahan Province Gas Company was reviewed using the pressure reduction station importance index, equipment failure risk, and reliability number to prevent unwanted failures and especially to help realize the strategy of continuing safe and sustainable gas supply and serving subscribers even in the coldest seasons of the year. The results of the present study include determining the station importance index from the perspective of the gas supply mission to subscribers; localizing the method of estimating the risk and consequences of station equipment failure; determining the reliability of station equipment; clustering and classifying regulators in the pressure reduction stations of the studied city's gas administration and functions based on risk and reliability parameters; determining the new frequency of maintenance operations based on the extracted information and according to the pressure reduction station importance index; ensuring the absence of unwanted and accidental failures and the availability of gas supply equipment within the expected time.

The suggestions extracted from this research include controlling the pressure regulation performance by regulators located in pressure reduction stations with a critical importance index that were placed in the first cluster and the consequences of their failure risk are relatively high through an online monitoring system in the dispatching center; controlling the pressure regulation performance by regulators belonging to pressure reduction stations with a semi-critical importance index that were placed in the first cluster, as well as regulators installed in critical pressure reduction stations that were placed in the second cluster through an offline monitoring system and a secure platform for discontinuous information transfer. The limitation of this research is the number of clusters considered, which is limited to three clusters, and it is suggested that a larger number should be investigated. Also, computer methods such as automatic clustering can be used to obtain the optimal number of clusters and provide clustering for planning. Another limitation of this research is the assumption that 166 regulators are in their useful life, so their failure has an exponential distribution function. It is suggested that the model be examined for new and worn equipment as well, meaning that by using the super-exponential, Weibull, and normal distributions, the failure of gas supply equipment in pressure reduction and measurement stations can be predicted, and a suitable maintenance program can be defined accordingly before the failure occurs. It is suggested for future research. Another important application of clustering is prediction for other devices, which is suggested for other regulators by having the RPN, RCM, and importance index of their troubleshooting planning. Finally, it is suggested that in future research, the presented method be applied to other station equipment such as shut-off valves, safety valves, etc.

Data Availability Statement

Data available on request from the authors.

Ethical considerations

The authors avoided data fabrication, falsification, plagiarism, and misconduct.

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Conflict of interest

The authors declare no conflict of interest.

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