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Original article

Optimizing pipeline integrity management through customized risk modeling: a case study in Kazakhstan

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ANNOTATION

Background: Nowadays industry best practices demonstrate that routine evaluation of pipeline risk enables more efficient resource allocation, particularly by focusing efforts on critical areas. Consequently, process of analyzing the risks associated with operating different facilities in petroleum industry should be considered a fundamental prerequisite for decision-making, especially while managing pipeline network's integrity. In the Republic of Kazakhstan, the current decision-making framework is founded upon the "technical condition" management model, which differs significantly from the risk-based approach prevalent in the international oil and gas industry. Moreover, as a result of the absence of the comprehensive failure statistics in the petroleum industry of the Republic of Kazakhstan, it makes it even more complicated to implement proper quantitative risk assessment.

Aim: This article aims to demonstrate how customized risk model can be developed to reflect specific conditions and challenges related with the working environment, dangers and threats, as well as data's quality and availability in Kazakhstan.

Materials and methods: QPRAM (quantitative pipeline risk assessment model), industrial data for the given pipeline X.

Results: The model illustrates fundamental and most important risk factors at high-resolution intervals along the pipeline's network and was calibrated using real data from the industry to ensure that the resulting risk profiles are reflective of the possible threats and existing operating experience in the given region.

Conclusion: Through the adoption of QPRAM's guiding concepts and methods, all parties in industry may strengthen operational resilience and safety standards against potential threats, protecting the long-term stability and dependability of critical infrastructure networks.

Keywords: *risk assessment; Quantitative Pipeline Risk Assessment Model; pipelines; hazards; threats; probabilities of failure; consequences of failure.*

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Оригинальное исследование

Оптимизация управления целостностью трубопроводов с помощью индивидуального моделирования рисков: тематическое исследование в Казахстане

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АННОТАЦИЯ

Обоснование. В настоящее время лучшие мировые практики демонстрируют, что оценка рисков трубопроводной системы позволяет более эффективно распределять ресурсы, особенно за счет сосредоточения усилий на критических областях. В результате анализ техногенных рисков, связанных с эксплуатацией объектов нефтегазовой промышленности, следует рассматривать как фундаментальную предпосылку для принятия решений по управлению целостностью трубопроводной системы. В Республике Казахстан действующая система принятия решений основана на модели управления техническим состоянием, которая существенно отличается от подхода, основанного на оценке рисков, распространённого в международной практике. Отсутствие всеобъемлющей статистики аварий на объектах нефтяной промышленности Республики Казахстан затрудняет проведение надлежащей количественной оценки рисков.

Цель. Цель статьи – продемонстрировать существенные преимущества интеграции количественной оценки рисков для повышения эффективности стратегий, используемых инженерами в сфере трубопроводного транспорта для предотвращения аварийных выбросов и снижения связанных с ними расходов на ремонт.

Материалы и методы. QPRAM (количественная модель оценки риска трубопровода), промышленные данные для данного трубопровода X.

Результаты. Модель демонстрирует фундаментальные и наиболее важные факторы риска в определённых интервалах вдоль сети трубопроводов, она была откалибрована с использованием реальных отраслевых данных для обеспечения адекватности полученных профилей рисков, берущих в расчёт возможные угрозы и существующий опыт эксплуатации в данном регионе.

Заключение. Путем принятия концепций и методов QPRAM, вовлечённые в отрасль лица могут укрепить операционную устойчивость и стандарты безопасности относительно потенциальных угроз, обеспечивая долгосрочную стабильность и надежность критически важных инфраструктурных сетей.

Ключевые слова: *оценка рисков, количественная модель оценки рисков трубопровода, трубопроводы, опасности, угрозы, вероятности отказа, последствия отказа.*

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Түпнұсқа зерттеу

Тәуекелдерді жеке модельдеу көмегімен құбырлардың тұтастығын басқаруды оңтайландыру: Қазақстандағы тақырыптық зерттеу

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АННОТАЦИЯ

Негіздеу. Қазіргі уақытта алдыңғы қатарлы салалық тәжірибелер құбыр жолдарының қатерлерін тұрақты бағалау аса маңызды учаскелерге назар аудара отырып, ресурстарды неғұрлым тиімді бөлуге ықпал ететінін айғақтайды. Осылайша, мұнай саласындағы әртүрлі объектілерді пайдалануға байланысты тәуекелдерді талдау, әсіресе құбыр желісінің тұтастығын басқаруда шешім қабылдау үшін негізгі шарт ретінде қаралуға тиіс. Қазақстанда шешімдерді қабылдаудың қолданыстағы жүйесі «техникалық жағдайды» басқару моделіне негізделген, бұл халықаралық мұнай-газ саласында қабылданған тәуекелге бағдарланған тәсілден айтарлықтай ерекшеленеді. Бұдан басқа, Қазақстанның мұнай-газ саласындағы ақаулықтардың кешенді статистикасының болмауы тәуекелдерді тиісті сандық бағалауды жүргізуді одан әрі қиындатады

Мақсаты. Зерттеудің мақсаты – жұмыс ортасына, қауіптер мен қауіптерге, сондай-ақ Қазақстандағы деректердің сапасы мен қолжетімділігіне байланысты ерекше жағдайлар мен проблемаларды көрсететін тәуекелдің жеке моделін әзірлеудің ықтимал жолдарын көрсету

Материалдар мен әдістер. QPRAM (құбыр қатерін бағалаудың сандық моделі), осы құбыр үшін өнеркәсіптік деректер X.

Нәтижелері. Модель құбыр желісі бойындағы рұқсаты жоғары учаскелерде негізгі және неғұрлым маңызды тәуекел факторларын көрсетеді және алынған тәуекел бейіндері ықтимал қатерлерді және осы өңірде пайдаланудың ағымдағы тәжірибесін көрсететініне көз жеткізу үшін саладан нақты деректер негізінде калибрленген.

Корытынды. QPRAM негізгі тұжырымдамалары мен әдістерін қабылдаудың арқасында саланың барлық қатысушылары дағдарысты инфрақұрылым желілерінің ұзақ мерзімді тұрақтылығы мен сенімділігін қорғай отырып, әлеуетті қауіптерге қатысты операциялық тұрақтылық пен қауіпсіздік стандарттарын арттыра алады.

Негізгі сөздер: *тәуекелдерді бағалау, құбыр жолдарының тәуекелдерін бағалаудың сандық моделі, құбырлар, қауіптілік, қауіп-қатер, бас тарту ықтималдығы, бас тартудың салдары.*

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Introduction

Pipelines play a crucial role in the petroleum industry, serving as the main tools for efficient transportation of crude oil, gas, and other refined products. Pipelines' extensive network facilitates are ensuring a reliable supply chain that is essential for sustaining the global energy demands all over the world. The pipeline network in Kazakhstan comprises both oil and gas pipelines, stretching across the country's vast territory with total length more than 35,000 km. These pipelines are essential for transporting crude oil, natural gas, and refined products from major production fields, such as the Tengiz, Karachaganak, and Kashagan fields, to refineries, ports, and neighbouring countries.

Evaluating the risks related with pipelines is a crucial step in ensuring the safe and reliable transportation. As the demand for energy continues to rise, so does the need for a comprehensive risk assessment framework. In this article, the importance of pipeline risk assessment will be discussed, as well as the likelihood and probability of events that will lead to a loss of integrity will be analysed together with the nature and severity of the consequences that might occur following a failure. Main goal of this article is to raise awareness about the importance of risk assessment of the pipeline's integrity, review the influencing factors and the proactive steps that can be taken in order to reduce the possibility of failure, preserve the environment, and ensure public safety.

Risk Model and NIMA software platform

Risk assessment is an analytical process, which involves the integration of design, construction, operating, maintenance, testing, inspection, and other information about a pipeline system. These data sets build the basis to measure the pipeline risk, which considers number of different aspects such as potential threats to that pipeline, possible failure scenarios and resulting consequences.

Early risk models were mostly based on simple scoring systems, that is why their nature was considered as semi-quantitative. However, since technical progress made it possible to have access to quantitative data sets from in-line inspection (ILI) and geographic information systems (GIS), as a result the risk models became more quantitative as well. One of such models is a Quantitative Pipeline Risk Assessment Model (QPRAM) that has been created to address potential risks using the systematic and analytical approach to evaluate and quantify possible threats within the pipeline networks. While including quantifiable data, this approach provides a more accurate picture of the consequences or likelihood of different pipeline-related events, going beyond qualitative judgments.

Implementation of QPRAM allows to generate a risk matrix for each individual threat at 1 metre intervals along a pipeline, while detailed analysis of the provided matrix is able to show managers and engineers how to maintain the integrity of the network. There is a specific flow chart, describing the risk assessment processes in QPRAM (Figure 1) [1].

At the first stage of QPRAM workflow, the identification of credible threats and failure scenarios is carried out, which consists in identifying and clearly describing all sources of hazards on sites where dangerous substances are handled and scenarios for their implementation.

In accordance with internationally recognised codes and industry practice, such as API RP 1160, following nine integrity threats are considered within the QPRAM:

- external corrosion (EC);
- internal corrosion (IC);
- manufacturing (M);

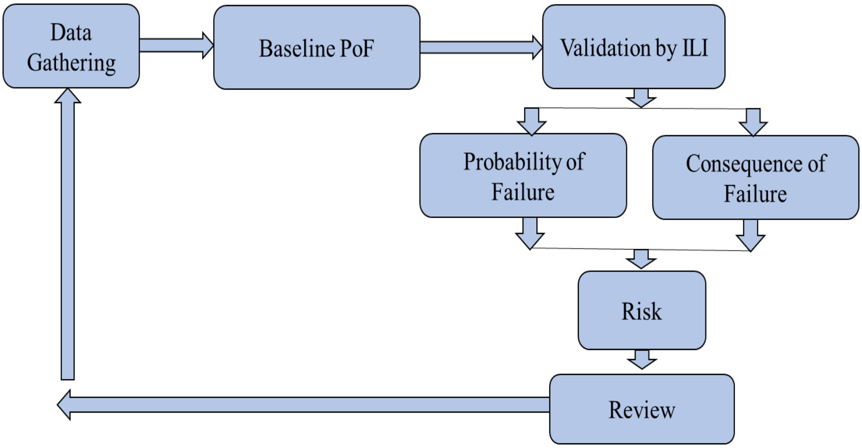

Figure 1. QPRAM Workflow – Schematic

- welding fabrication (WAC);
- third party damage (TPD);
- stress corrosion cracking (SCC);
- equipment (E);
- incorrect operations (IOF);
- weather/external forces (WEF) [2].

Although an oil pipeline may be highly exposed to one or more threats, this fact is not necessarily meaning that any particular threat or combination of threats will lead to serious consequences. There are numerous potential scenarios for pipeline failures, many of which involve leaks of oil or petroleum products and the risk of ignition. In other words, one cannot be sure that if an oil pipeline fails, it will fail in a certain way, therefore it is crucial to consider possible failure scenarios and determine the probability of each scenario to be realized.

The approach adopted in the QPRAM model is limited to the establishment of 4 possible failure scenarios for the development of an accident for the above threats, depending on the possibility of manifestations of damaging factors:

- leak with no ignition;
- leak with ignition;
- rupture with no ignition;
- rupture with ignition.

At the second stage of the risk analysis, an assessment is made of the baseline probability (frequency) of the failure (BPoF) due to the influence of previously established integrity threats based on the statistical data of the network. At the third stage, segmentation (division) of the analyzed pipeline into conditionally homogeneous components (dynamic segments) is performed using various external and internal factors (initial data) that affect the basic probability of failure for a specific threat and change along the route. At the fourth stage, the probability of PoF failure is calculated for each individual pipeline segment. The calculation uses the principle of adjusting the average (basic) probability of failure on the pipeline using a specially built system of groups of influence factors with expert-determined weighting coefficients and scales of factor scores. This approach considers the unequal influence of natural and climatic conditions, technical and technological, operational, service life, anthropogenic and other factors on the possibility of depressurization.

The next, fifth stage of the risk analysis is the assessment of possible consequences for the considered accident scenarios, which can be conditionally grouped by the time of their occurrence in relation to the accident:

1. in case of an accident;
2. after the accident (time: a short period);
3. after the accident (time: an extended period).

The final stage of the work is the calculation of man–made risk R, which is a measure of danger characterizing the possibility of an accident and the severity of its consequences, and is calculated using the following formula (1):

$$R = PoF \cdot CoF \qquad (1)$$

where

PoF is the probability of failure (frequency);

CoF is damage from an accident, in US dollars;

R is a risk value (expected annual damage, considering the frequency of accidents on pipelines), US dollars.

ROSEN's Asset Integrity Management Software suite (NIMA) is used to manage the process of pipeline's data integration and the implementation of QPRAM. Using this approach enables the main operator to identify and compare the risks existing on their pipeline's segments. As well as that, QPRAM's results make it possible to focus on the elevated risk areas, assessing the benefits of implementation of preventive measures. Correctly managed data and attentively evaluated risks provide additional benefits such as consistency and traceability.

CASE STUDY

Pipeline and pipeline data sets overview

The Quantitative Pipeline Risk Assessment Methodology was used to calculate and analyse existing risks for the case of an oil pipeline X, located in Kazakhstan; the characteristics for chosen pipeline are shown in Table 1 [3].

One of the most crucial and fundamental inputs for this model is historic failure frequency, that is why it should ideally reflect pipeline network's local conditions and expected consequences. But, if this data is not available due to any circumstances, regional statistics with similar environmental conditions could be used. Considering the short service life of the pipeline X, and, as a result, a small number of failures, it was proposed to apply publicly available regional failure statistics [4].

Table 1. Pipeline X characteristics

Section	Length (km)	Construction date (year)	Diameter (inch)	Wall Thickness (mm)	Pipe Material	Design pressure (MPa)
1	225	2008	32	8	X60	6.3

Threat Analysis (PoF)

In the following case of pipeline X essential calculations of external corrosion and TPD are showed as an example.

1. External corrosion (EC)

During the assessment of the external corrosion, the main route conditions such as existing of rivers and crossings, the effectiveness of passive and active protection and other soil corrosion intensifying factors (soil corrosion activity, waterlogging, the presence of other underground metal structures) must be considered.

In the given case, for the pipeline X 73 segments were obtained based on the results of dynamic segmentation according to parameters characterizing the effect of external corrosion on the probability of failure. The average probability of failure for this threat is 7.41×10^{-9}.

Based on the PoF values 8 most susceptible to external corrosion threat pipeline segments have been identified (Table 2). The main parameters contributing to the increase in the probability of failure in individual segments are the lack of corrosion inspection results, the intersection of pipelines with railway lines and power lines (Figure 2). The qualitative assessment of the degree of danger of this threat to the integrity of the pipeline in % of the total probability of failure is 1.09%.

2. Third Party Damage (TPD)

This group examines external factors that may impact the PoF caused by third parties to the pipeline under consideration. Factors such as high population density in adjacent areas, levels of industrial and economic activity, and intersections with various infrastructure pose threats to the integrity of the system [5].

A total of 97 segments were identified along Pipeline X, spanning 225 kilometres, through dynamic segmentation based on parameters indicating the third-party damage (TPD) risk

Table 2. Pipeline X characteristics

#	Segment	Distance, km	PoF	Key Factors	
1	H	69	4.19E-08	No corrosion Inspection data	The pipeline is crossed by a power line, measures to reduce the effects of alternating current have not been implemented
2	I	76	2.25E-08		Railway crossing
3	J	76.1	2.25E-08		
4	K	79	4.19E-08		The pipeline is crossed by a power line, measures to reduce the effects of alternating current have not been implemented
5	L	93	2.25E-08		Railway crossing
6	M	93.5	2.25E-08		
7	N	200	4.19E-08		The pipeline is crossed by a power line, measures to reduce the effects of alternating current have not been implemented
8	O	214	4.19E-08		

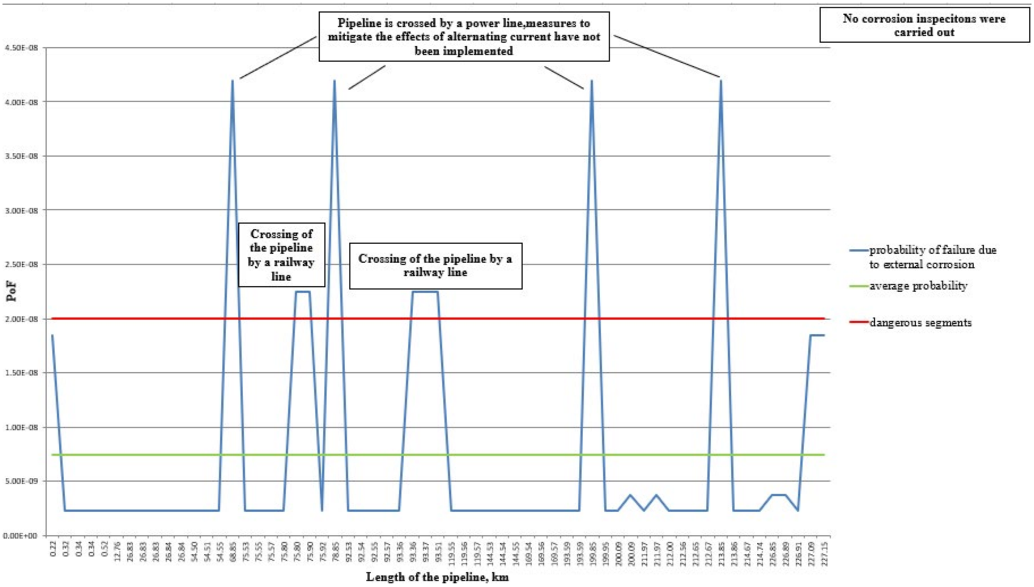

Figure 2. Probability distribution of failure due to external corrosion (EC)

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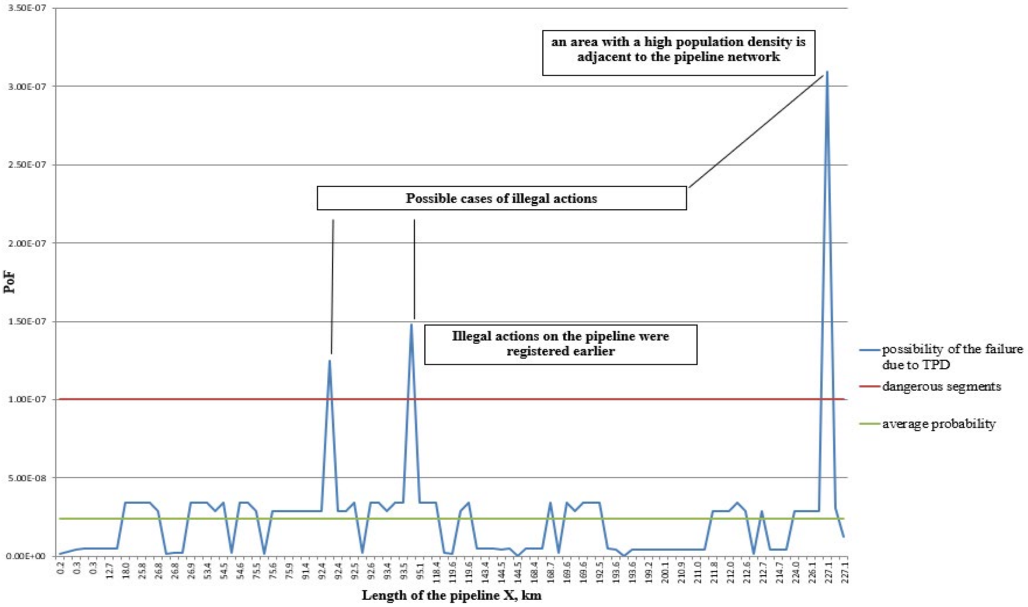

Figure 3. Probability distribution of failure due to third party damage (TPD)

and potential of its impact on the probability of failure. The graph depicting the probability distribution of failure due to third-party damage (TPD) along Pipeline X is illustrated in Figure 3. On average, the probability of failure attributed to this threat is 2.4×10-8.

Based on the PoF values 3 most susceptible to TPD threat pipeline segments have been identified. The main parameter contributing to the increase in the probability of failure in certain segments is a violation of the pipeline's security zone – unauthorized crossings through the pipeline (Figure 3).

The qualitative assessment of the degree of danger of this threat to the integrity of the pipeline X showed that the total probability of failure is 3.5%.

Consequences Analysis (CoF)

In order to understand main consequences of the failure, two crucial aspects such as economic impact and impact on surrounding population were taken as basis for the following calculations.

1. Economic impact (ECON)

The assessment of direct damage to production considers the complete or partial destruction of a property object. This assessment encompasses the full cost of restoring the object, including various components such as:

The cost of product losses incurred due to the accident.

Lost revenue during emergency downtime.

The expenses associated with repairing the damaged object.

The cost of re-commissioning the object to resume operations.

These factors collectively contribute to the overall evaluation of direct damage to production resulting from a failure (Table 3–4).

Table 3. List of parameters used in the ROAIMS risk model to calculate direct damage to production

Parameter	Value
The cost of transporting a unit of production (USD/barrel)	1.62
Volume flow rate (bbl/h)	9353
Oil pipeline workload (h/day)	24
Estimated income (USD per week)	2553177

Table 4. The results of the calculation of direct damage to production for the pipeline's site

Accidents (scenarios)	S1	S2	S3	S4
Direct damage, USD	258966	350160	669364	851733

2. Impact on the surrounding population (PPLE)

The socio-economic damage resulting from an accident at Pipeline X includes the following factors: loss of life, injuries to personnel at the network's facilities, and the possible damage towards the individuals living in areas surrounding the site.

To quantify the socio-economic damage for a specific segment of the pipeline network, the expected number of accident victims is multiplied by costs associated with each individual

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(Figure 4). These costs incorporate compensation payments and benefits provided to victims and/or their relatives. The estimate of these costs, as utilized in the ROAIMS risk model, varies depending on the severity of injuries sustained by individuals involved in the accident [6].

Risk Analysis (R)

In order to be able to construct a comprehensive and well-structured plan for the preventing actions, addressing mostly zones with an increased risk, the sensitivity analysis must be performed based on the identified primary risks. It also must be noticed, that the input data used in the model must undergo the quality control before being implemented. Additional data collection and verifications of the existing inputs must be used to ensure reduction of the uncertainty of the analysis.

The Figures 5 and 6 are displaying the Risk calculation results for the case of pipeline X.

From the Figure 6 it can be seen that the highest risk values is localized at approximately 75th km and 93rd km of the pipeline

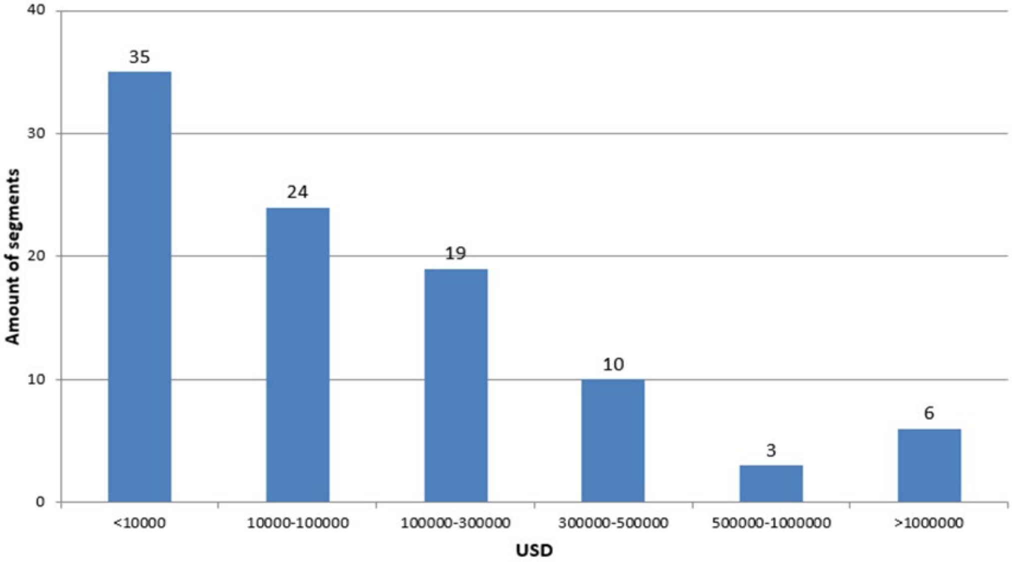

Figure 4. Distribution of socio-economic impact by number of segments (PPLE)

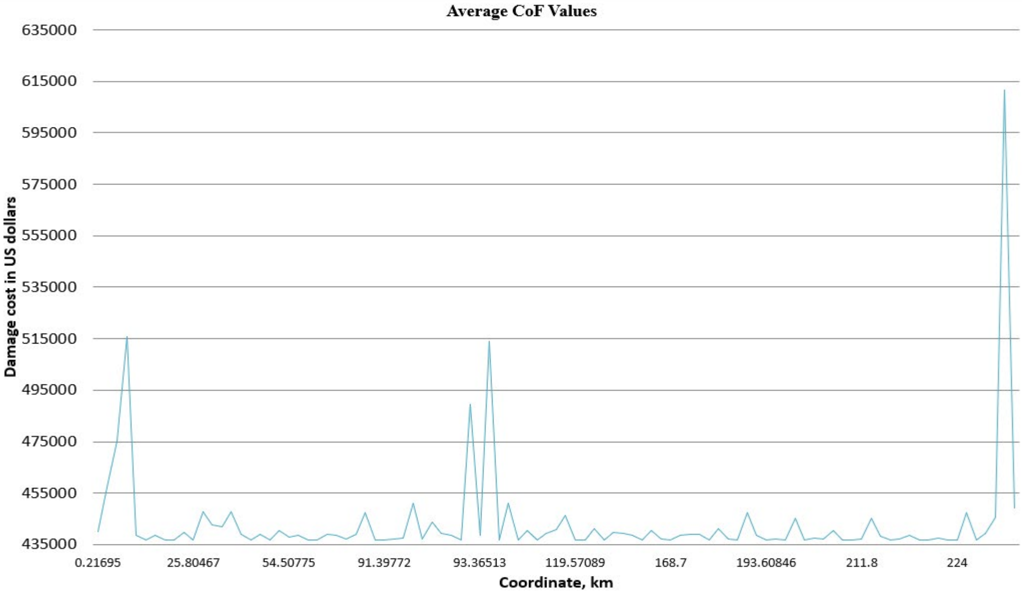

Figure 5. Average CoF values

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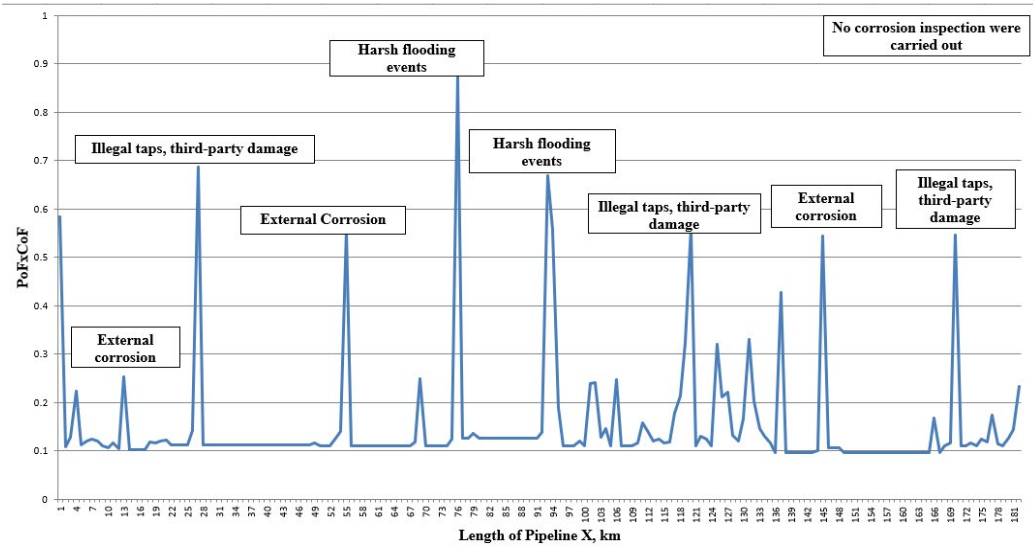

Figure 6. Distribution of the risk index R along the pipeline

and is equal to 0.9. The reason behind it is that according to the calculations the mentioned section is more likely to face harsh flooding events, having a relatively high likelihood of failure due to weather conditions. Other sections with relatively high risk of failure are located close enough to residential areas, and as a result they are more likely to be damaged by third-party and have higher risk of illegal taps occurrence. Thus, it would be rational to prioritize resources to mitigate this threat as soon as possible. The line graph at the Figure 6 shows that corrosion inspections were absent across the entire pipeline, that is why it is essential to note that there is a huge number of segments with a high likelihood of failure due to the external corrosion [7].

Overall, any measures towards the risk mitigation and reduction would have a significant effect on the all pipeline network's integrity [8]. As it was already stated previously, the main goal of the pipeline's operator is to focus on reducing the frequency of failure by preventing the development of the threats at the early stages. Since it is more rational to reduce risks rather than reducing consequences [9]. QPRAM therefore helps to identify which hazards increase the risk of failure, making it possible to define a strategy to mitigate them beforehand.

Table 5 illustrates an overall view of the risk profiles of the all threats: internal corrosion, external corrosion, manufacturing, welding fabrication, stress corrosion cracking, third party damage, equipment, incorrect operations, weather/external forces. According to the generalized results of calculations, the pipeline X has almost impossible risk of failure.

Table 5. Distribution of the risk index R along the pipeline

CoF	PoF				
	frequent failure	**probable failure**	**possible failure**	**rare failure**	**almost impossible failure**
catastrophic	🟥	🟥	🟥	🟥	🟧
critical	🟥	🟥	🟧	🟧	🟨
not critical	🟥	🟧	🟧	🟨	🟨 Pipeline X
moderate	🟨	🟨	🟨	🟩	🟩

Conclusion

To summarize, implementing a quantitative risk assessment technique in industrial environments has several benefits, such as extending the lifetime of equipment and proactively identifying and mitigating possible dangers. The implementation of QPRAM addresses a critical achievement with regards to the Kazakhstan pipeline industry. This study project, which is a first for the pipeline sector in Kazakhstan, is a big step improving the risk management practices in the existing area.

The usage of profoundly adaptable software for considering the qualities and details of the pipeline framework highlights the obligation to accuracy and adequacy in risk assessment. Furthermore, this quantitative risk assessment model's core flexibility makes it possible to effortlessly integrate various data inputs, which makes it easier to fully understand prospective risk situations. Through the adoption of QPRAM's guiding concepts and methods, all parties in industry may strengthen operational resilience and safety standards against potential threats, protecting the long-term stability and dependability of critical infrastructure networks.

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