UNIVERSITY OF PETROSANI

DOCTORAL SCHOOL
DOCTORIAL FIELD: ENGINEERING AND MANAGEMENT

DOCTORIAL THESIS

DOCTORAL SUPERVISOR:

Prof.univ.dr.habil.ing.ec. POPESCU Cătălin Nicolae

DOCTORAL STUDENT:

ANGHEL (VLĂDESCU) Elena Cristina

2025

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Contributions to the development of predictive management systems aimed at improving predictive maintenance technologies for pipeline transportation infrastructures of liquid hydrocarbons

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DOCTORAL THESIS SUMMARY

Contributions to the development of predictive management systems aimed at improving predictive maintenance technologies for pipeline transportation infrastructures of liquid hydrocarbons

Research context and motivation

In Romania (due to the lack of official reporting of the number of failures in crude oil pipelines), the assessment of these accidents, especially their classification, is deficient.

The classifications currently in place indicate that the failures are due to:

- Forces external to the pipeline transport system,
- Corrosion phenomena,
- Other defects caused by the pipeline location environment,
- Defects caused by the operator,
- Defects in the pipeline material,
- Welding defects,
- Defects in pressure measurement equipment and/or integrity control of pipeline transport systems.

In recent times, due to the growing concerns regarding the effects of emissions due to the combustion of petroleum products on the environment, and especially the increase in the population's requirements regarding environmental protection (followed by the tightening of legislation), the need has arisen to implement a pipeline integrity management system (based on the adaptation of advanced inspection and monitoring technologies necessary for the early detection of defects) and to introduce predictive management methods aimed at improving anticipatory maintenance technologies.

The extremely serious consequences of defects and the costs associated with remediation make the prevention and limitation of the effects of incidents absolute priorities.

This trend favors the adoption of repair techniques that reduce the risk of leakage during the intervention and reduce the ecological footprint of the operation (for example, excavation-free repairs, the use of composite sleeves).

The operation and maintenance of extensive crude oil pipeline networks are complex processes that are subject to a variety of inherent challenges and risks.

In essence, the causes of pipeline system failure are:

a. Corrosion, which continues to be one of the most important threats to pipeline safety;
b. Pipe material failures are due to the pipe manufacturing process (defects in the pipe body or in the longitudinal/helical weld;
c. Weld failures can occur during construction (non-compliant circumferential welds, inadequate installation);
d. Failures of ancillary equipment (valves, fittings, gaskets or control systems) are also a significant cause of incidents;
e. Third-party failures are defined as accidental interventions by third parties in the pipeline safety zone, in particular through excavation or construction activities;
f. Bends caused by impacts or the placement of pipelines in areas with gravel or hard rocks are particularly dangerous and are subsequently accompanied by loss of material;
g. Natural phenomena (geological hazards) represent another relevant source of external damage;
h. Non-compliant operation and/or human error in operating the system are mistakes made during normal operation or in abnormal situations and can lead to serious incidents; accidental over-pressurization, inadequate pressure or flow control, failure to comply with operating or maintenance procedures and erroneous decisions in emergency situations are common examples;
i. Cracking of the pipe material due to the appearance of internal stresses; these stresses may be due to stress corrosion or cracks due to material fatigue;
j. Embrittlement of the pipe material (it is a determining phenomenon in the case of main crude oil pipelines);
k. Unauthorized interventions on the crude oil transportation system.

As we have specified above, failures of crude oil pipelines also lead to the triggering of a wide range of operational, ecological and safety hazards, with a potential severe impact on the environment.

These are:

- Safety hazards
- Environmental hazards
- Economic hazards
- Social hazards.

As such, pipeline transportation systems face exceptional challenges in terms of their maintenance, determined including by:

a. Age of pipelines

b. Difficult access and hostile environments

c. Romania's urban development strategies

d. Compliance with applicable legislation

e. Technological limitations

f. Data management and analysis

g. Skilled workforce

h. Cost and resource management.

Against this background, we have further conducted a critical analysis of current inspection and monitoring technologies.

The oil pipeline industry benefits from local detection systems for wall thickness and insulation condition, as well as intelligent instruments that detect the condition of pipelines by scanning their interior.

Thus, non-destructive testing (NDT) has as its main methods:

i. Testarea ultrasonică (UT);

j. Testarea ultrasonică cu unde distribuite pe distanțe mari (GWUT);

k. Inspecția cu scurgeri de flux magnetic (MFL);

l. Utilizarea de traductoare acustice electromagnetice (EMATs);

m. Testarea cu curenți turbionari (ECT);

n. Emisia acustică (AE).

NDT assessments also include in-line ILI (continuous flow pipeline inspection) inspections using Intelligent PIGs:

a. MFL (Magnetic Flux Leakage) PIGs:

A variant of Transverse Field Inspection (TFI), it uses a different orientation of the magnetic field and is sometimes used to detect certain types of longitudinally oriented cracks or defects;

b. UT (Ultrasonic Testing) PIGs: Uses ultrasonic transducers to directly measure the remaining wall thickness of the pipe.

c. Caliper PIGs: These instruments are equipped with flexible mechanical arms or electromechanical sensors that measure the internal diameter of the pipe along its entire length.

d. PIGs for crack detection:

The standard that defines the application of In-Line technologies is the API Std 1163 standard, which establishes performance-based requirements, defining key points such as Probability of Detection (POD), Probability of Identification (POI) and Sizing Accuracy (SA).

As in any field, there are limitations and challenges for non-intrusive inspection (NDT) technologies:

a. Piggability

b. Data quality

c. Accuracy of defect detection and sizing

d. Cost.

In this general context, the central motivation of the research contained in the doctoral thesis arose, namely the identification, verification and proposal of modern tracking and control techniques that would manage the suite of means listed above in an integrated manner in order to increase the degree of operational safety of hydrocarbon transport systems.

Research objectives

This doctoral thesis is intended to be a first specialized work that analyzes:

a. Use of fuzzy control techniques in ensuring pipeline maintenance;

b. Statistical analysis of the expenses necessary for the maintenance of a pipeline system;

c. Study of predictive methods for pipeline maintenance;

d. Risk assessment during operations to ensure the security of crude oil pipelines;

e. Analysis of the medical sensitivity of employees working in the field of crude oil pipeline maintenance within the national company for the transport of petroleum liquids through pipelines;

The work has a strong applied character, being the first in the world to analyze:

a. The role of petroleum fluid transport pipelines in ensuring the energy security of NATO member countries;

b. How to increase operational safety by using modern tracking and control techniques;

c. Environmental challenges in the context of the transition to reducing greenhouse gas emissions and using energy resources from renewable sources;

d. Decarbonization of the Romanian national petroleum liquid transport system, by analyzing the allocation of pipelines for the transport of carbon dioxide.

The paper also aims to gain a deeper understanding of the determinants of damage and their impact on economic costs, in order to develop effective prevention policies, improve maintenance strategies and optimize resource allocation to reduce losses in the pipeline transport sector.

Research methodology

The research methodology included the use of advanced analysis techniques such as Kolmogorov-Smirnov and Shapiro-Wilks normality tests, analysis of variance (ANOVA), Kruskal-Wallis test, multiple linear regression and decision tree models (CHAID). By using statistical methods, predictive maintenance helps companies reduce risks, optimize costs and extend the life of pipelines, thus contributing to a more efficient management of crude oil transportation networks. The study focuses on the structure and distribution of failures, the geographical distribution of failures, the economic impact of failures, the seasonality of failures, correlation analysis and cost factor modeling.

For the research methods addressed, we used reports, previous experimental studies, longitudinal studies and transdisciplinary studies, we collected and analyzed numerical data, with the emphasis on measuring the scale, range, frequency of the stated phenomena, we created simulation models for analyzing the instantaneous risk rate of a pipeline system, quantitative risk assessment (Quantitative Risk Assessment - QRA), using mathematical models and statistical data.

The variables in the research were selected in such a way as to ensure the best possible analysis of the aspects related to the causes of losses and damages in the sector.

The data regarding the total cost and the average monthly cost in lei were converted into USD based on the average monthly exchange rate published by the NBR on its website for a better comparison of their evolution during the analyzed period.

For the continuous (numeric) variables, it was verified using the One sample Kolmogorov – Smirnov test whether the values follow a normal distribution, at the level of the entire sample of statistical records, in order to subsequently choose the appropriate statistical instruments and methods.

From the presented results it was deduced that for none of the continuous (numeric) variables there is a normal distribution and therefore non-parametric statistical methods appropriate to "non-normal distribution" data were used.

Since for the data analysis comparisons were made between or within a group (for example, comparisons of differences between years, between months, type of damage, etc.), the normality of the distribution of values for continuous variables in the research was tested using the Shapiro – Wilks test.

To analyze whether there are correlations, associations between the variables in the research, we applied the non-parametric Spearman and Pearson correlations for the categorical variables in the study.

To analyze whether there are significant differences in the number of damages recorded in a month, the total cost in lei and / or dollars in a month or the average cost per month in lei and / or dollars, we applied the One – way ANOVA method with Bonferronni correction and the Kruskal – Wallis test for independent samples with paired comparisons to identify exactly between which subgroups these statistically significant differences exist.

This result is also confirmed by the results of the ANOVA test for comparing the means of these variables between the study years, and the Bonferroni test does not indicate differences between any comparative pair of years.

However, the Bonferroni pairwise comparison test did not indicate any statistically significant difference between the types of damaged products.

In order to identify which is the best predictor or the variable that best differentiates between values below or above the average cost, we applied the "decision tree" method with the CHAID algorithm, the results being presented graphically.

In conclusion, the implementation of a well-structured preventive and predictive maintenance system will not only reduce the risks of failures, but will also optimize operational costs, ensuring the safe and efficient operation of the infrastructure in the long term.

Thesis structure

In summary, the doctoral thesis is structured in two consistent directions:

"Analysis of crude oil pipeline transport systems in Romania",

broadly developed in:

- Chapter I "Analysis of maintenance systems of liquid petroleum pipelines";

- Chapter II "Current status in research on the repair management of crude oil pipelines";

- Chapter III "Statistical modeling of operating expenses of the national crude oil pipeline operator";

- Chapter IV "Risk modeling in the repair management of crude oil pipelines",

Respectively,

"Contributions on the optimization of the maintenance of crude oil pipeline transport systems in Romania",

detailed in:

- Chapter V "Application of waiting lines and fuzzy elements in the repair of petroleum fluid pipelines";

- Chapter VI "Predictive maintenance of systems subject to major failures, based on the proportional risk model";

- Chapter VI "Modeling of greenhouse gas emissions from crude oil leaks following damage".

Research results

Effective repair management cannot be separated from broader pipeline integrity management (PIM) and safety management systems (PSMS) strategies.

These modern techniques provide a structured and proactive approach to identifying, assessing and mitigating risks throughout the pipeline's life cycle, informing decisions regarding inspections, maintenance and repairs.

Pipeline Integrity Management (PIM) is defined as a systematic, comprehensive and integrated process designed to assess and mitigate risks associated with pipeline operations, thereby ensuring their safety and reliability.

A typical PIM program involves a continuous cycle of activities:

Risk Identification: Recognizing all potential hazards that could affect the integrity of the pipeline (e.g. corrosion, mechanical damage, material defects, natural forces, operational errors);

Data Collection and Integration: Gathering all relevant information about the pipeline (construction characteristics, operational history, inspection and monitoring data, environmental conditions);

Risk Assessment: Analyzing data to estimate the probability and potential consequences of a failure for each pipeline segment, allowing for prioritization of high-risk areas;

Integrity Assessment: Using appropriate inspection methods (e.g. ILI, direct assessment, hydrostatic testing) to determine the current condition of the pipeline, especially in high-risk areas or areas with potential high consequences (HCA);

Repairs and Preventive Measures (P&MM): Implementing the necessary actions to correct identified defects (repairs) or to reduce the probability or consequences of a failure (preventive measures, such as improving cathodic protection, or mitigating measures, such as installing quick-closing valves);

Performance Evaluation and Continuous Improvement: Monitoring the effectiveness of the PIM program through performance indicators (metrics) and continuously adjusting strategies and processes based on results and lessons learned.

In the dimension of improving pipeline safety management systems (API RP 1173 Standard), which aims to proactively and systematically manage safety risks in all operational and decision-making aspects of the company, we created an AI model to develop a safety management platform.

The key components of the platform are:

1. **Operational Control Panel:**

   o Interactive Map: A visual representation of the pipeline network in Romania;

   o Real-Time Information: (pressure, flow and static risk level of the respective area)

2. **Artificial Intelligence Engine (Simulated):**

   o Anomaly Detection;

   o Smart Alerts;

3. **Predictive Maintenance:**

o Risk Graph: This graph is updated in real time and shows the probability of failure estimated by an AI model (simulated) for each segment in the next six months.

o Decision Making: This tool allows maintenance teams to prioritize their efforts, focusing on the segments with the highest risk of failure, before an incident occurs.

Regarding risk assessment and risk modeling in the operation of a pipeline system, we started from:

1. analysis of the pipeline condition (operating pressure) depending on the wall thickness;

2. evaluation of metal defects and their classification by five intervention classes;

3. evaluation of insulation defects and their classification by five intervention classes;

4. integration of data on the state of the environment (geological data, meteorological data, etc.);

5. risk analysis of damage to an oil pipeline;

6. creation of a risk assessment model based on artificial intelligence;

7. optimization of the model.

Within this model we used:

1. pipeline condition databases;

2. Monte Carlo simulation to assess the uncertainty and distribution of possible accident outcomes;

3. Modeling the dispersion of both crude oil and volatile organic compounds;

4. Assessing the risk to the health of employees and contractor personnel;

5. Assessing the risk of accidents of oil pipelines on the environment (buildings, etc.).

In this PhD thesis, I wrote a Python program on risk assessment in the operation of crude oil pipelines.

The Python script demonstrates a simplified approach, based on a model that uses risk definition scores.

When the numerical risk is greater than 60, the activity is critical, for a value greater than 35 and less than 60 the risk is high, for a value greater than 15 and less than 35 the risk is medium and below 15 the risk is low.

I transferred the model I proposed previously into a model that uses artificial intelligence (AI).

The model I developed in AI starts from the definition of a pipeline system (a large set of historical data about the pipelines, including which ones have had failures and which have not).

For this chapter, I generated the software for calculating the operational risk through Machine Learning by:

1. Simulating over 1000 pipeline segments;

2. Including their properties and the number of failures per section;

3. Using the RandomForestClassifier algorithm, trained on 80% of the data we entered;

4. Evaluating the model performance (on the remaining 20% of pipelines that are new segments);

5. Obtaining data on the most important factors in predicting a failure (e.g. pipeline age or environmental corrosion).

The model described by calculating the risk is based on elements defined by the expert who makes the prediction.

The one defined with the help of AI learns on its own what are the hidden patterns and correlations in the data with a high risk of damage.

The output data consisted of:

1. Classification reports (in the console);

2. Confusion matrix graph (this graph is essential to understand the type of errors each model makes);

3. ROC curve graph;

4. Factor importance graphs.

The software runtime data is presented in Annex no. 1 of this summary.

Next, we addressed, with the aim of improving, the issue of analyzing pipeline systems using queues.

Queue theory, also known as queuing theory, is a field of applied mathematics that studies waiting lines or queues.

This is essential in the context of repairing oil pipelines, where efficient resource management and repair times are critical for optimal operation.

Queue theory is based on mathematical models that describe the behavior of queues.

These models use variables such as arrival time, service time, number of servers, and queue capacity.

The most common models include:

- M/M/1 (single queue with Markovian arrivals and services);
- M/M/c (multiple servers with Markovian arrivals and services);
- M/G/1 (single queue with Markovian arrivals and general services).

Being the most complex, it approached, for improvement, the M/M/c model.

In the model we defined:

• M (Markovian): Describes the process of failure occurrence and assumes that failures occur randomly over time, but at a constant average rate.

The time between two consecutive failures follows an exponential distribution.

• The second letter M (Markovian): Describes the process of repairing the pipeline. It assumes that the time required for a repair also follows an exponential distribution. All "c" maintenance teams are assumed to be identical in terms of their average working speed.

• c: Represents the number of servers (maintenance teams) available to perform the repairs.

And at this stage of the doctoral thesis I created a software program that combines queuing theory with artificial intelligence (AI).

Given that an M/M/c model is based on fixed probability distributions, and an AI program can use historical data to make specific predictions, thus improving the accuracy of the simulation, the software created is a machine learning model that predicts the time required for a repair, based on some characteristics of the failure, instead of using a fixed average service rate.

This program is a simulation, not just a calculation of formulas, the key steps being:

1. Synthetic data: The program creates a training dataset that links the type of failure and location with a repair time. This simulates the historical database that a maintenance company has.

2. AI model: A simple linear regression model from the scikit-learn library is trained on this data. Its role is to predict how long a repair will take.

3. Simulation: The program simulates the occurrence of failures (at random intervals) and asks the AI model to predict the repair time, then places them in a queue for maintenance teams.

4. Results: At the end of the simulation, indicators such as the average waiting time and the average number of failures in the system are calculated.Acest program demonstrează cum un model de AI poate oferi o estimare mai granulară și mai realistă a timpului de service, făcând simularea mult mai precisă.

In the next chapter, we addressed predictive maintenance of systems subject to major failures, based on the proportional hazards model.

The role of this work technique is to anticipate failures before they occur. Predictive maintenance uses real-time data and statistical models to estimate the likely time of a failure.

A particularly powerful statistical methodology in this context is the proportional hazards model (COX model), which allows the analysis and prediction of major failures by identifying risk factors that influence the lifespan of a system.

In conclusion, this methodology transforms raw data, collected by sensors, into a strategic risk management tool, ensuring a safer, more efficient and more cost-effective operation of critical transport infrastructure.

We created a model for CONPET in the COX system.

For this pipeline system, we generated, in stage I, an AI program for 2500 historical data and divided the model into 2000 training points and 500 test points (figure 6.2).

We used all four AI tests, namely Linear Regression, Random Forest, XGBoost and Neural Network.

The performances were expressed by MSE (lower means better) and we obtained for:

- Linear Regression : 0.001923;
- Random Forest : 0.001040;

- XGBoost : 0.001057;

- Neural Network : 0.001109.

In the second stage of this study, we created a simulation model with 2000 data points simulating the problems that can affect the integrity of crude oil pipelines, namely:

a. Illicit activities;

a. Cathodic protection status;

b. Soil aggressiveness;

c. Pipeline age;

d. Poor maintenance funding;

e. Poor management;

f. Material defects;

g. Control equipment failure;

h. Pipeline material failure.

The program I created using Cox methods returned the time to failure (days).

In the third stage, I created the Survival Curves (an extremely intuitive graph).

This program provides us with a complete and robust analysis, exactly as a data analyst in an oil and gas company would do to prioritize inspections and repairs.

I also generated in an AI program the selection of the best model in assessing the effects on pipeline damage.

I generated over 2000 damage points obtaining:

- Linear Regression : 18287.353611;
- Random Forest : 20300.916058;
- XGBoost : 24616.211764;
- Neural Network : 17477.628347.

Interpreting the graphical results led to the conclusion that, although using a completely different approach, advanced AI models can successfully "rediscover" the main risk factors from a complex data set, providing results aligned with those of classical statistical methods, but with potentially greater flexibility.

Next, we analyzed ways to model greenhouse gas emissions from spilled crude oil following accidents.

Although there are not many numerical modeling relationships in the specialized literature, I managed to create some numerical relationships based on linear regression data by determining the quantities of crude oil spills in the field and especially by measuring the emissions of various compounds.

Linear regression is a "transparent" (white box) model that produces a simple and directly interpretable mathematical equation.

SVR, Random Forest and Gradient Boosting models are "black box" models.

They are often much more accurate, but do not produce a simple algebraic formula.

Their prediction is the result of a complex algorithm, represented as a function f(variables).

Advanced models (SVR, Random Forest, Gradient Boosting) provide a more accurate prediction through complex modeling of H_2S volatility depending on the physical properties of crude oil.

Conclusions and future research directions

Despite all the progress made, a number of significant challenges and areas requiring further research remain:

- **Managing Aging Infrastructure**: Effectively managing the risks associated with aging pipelines, which constitute a significant part of the global network, remains a major technical and economic challenge.
- **Detecting Complex Defects**: Reliable detection and sizing of certain types of defects remains difficult. Complex cracks (e.g. SCC colonies, interacting cracks, cracks in areas with complex geometry or high residual stresses), certain weld defects, or early stages of corrosion or mechanical deterioration may escape detection or be incorrectly sized by current technologies.
- **Unpiggable Pipelines**: A significant proportion of existing pipelines cannot be inspected by conventional ILI methods due to geometric or operational constraints. The development and validation of alternative inspection methods (e.g. enhanced direct assessments - ECDA) or new technologies (e.g. internal inspection robots) for these segments are essential.
- **Data integration and validation:** Effectively combining data from multiple and heterogeneous sources (ILI with different technologies, NDT, sensors, operational data, history) into a coherent and reliable risk model is an ongoing challenge. Ensuring data quality, quantifying uncertainties, and managing missing or incomplete data are critical

issues.

● **Long-term performance of new materials:** Although composite repairs are standardized, validating their durability and performance over very long terms (decades) under real operational and environmental conditions requires the accumulation of field data and further research into long-term degradation mechanisms.

● **Human factors and safety culture:** Human error remains a significant contributor to incidents. Implementing and maintaining a robust organizational safety culture that encourages vigilance, open communication, and continuous learning is an ongoing and essential process.

● **Economic profitability:** Finding the optimal balance between the investments required to implement advanced inspection, monitoring and repair technologies and comprehensive PIM/PSMS programs, and operational budget constraints, remains a constant managerial challenge.

Future trends and research directions

The future of pipeline repair and integrity management appears to be shaped by the convergence of several technological and strategic trends:

- **AI/ML Integration**: An increasing use of artificial intelligence and machine learning is anticipated throughout all stages of the PIM cycle. This includes more sophisticated algorithms for automated analysis of NDT and ILI data for defect detection and characterization, more accurate predictive models for degradation estimation, optimization of risk assessments, and development of intelligent decision support systems for operators.
- **Digital Twin**: The concept of creating a detailed virtual replica of the physical pipeline, updated in real time with sensor and inspection data, is gaining traction. Digital twins allow for the simulation of pipeline behavior under various operational or failure scenarios, optimization of predictive maintenance strategies, risk visualization, and virtual testing of interventions.
- **Advanced Robotics:** Continued progress is expected in the development of robots for inspection and repair, with a focus on increasing autonomy, navigation in complex environments (non-pigable pipelines, underwater), dexterity of manipulators and the range of tasks they can perform (e.g. welding, composite application, advanced NDT).
- **Improved Sensors and Monitoring:** Research focuses on the development of more

sensitive, reliable, cheaper and easier to deploy sensors (including wireless and self-powered sensors) for continuous monitoring of key parameters of the pipeline and the surrounding environment. Remote sensing technologies (satellite, drones) will benefit from better spatial and temporal resolutions and more powerful image analysis algorithms.

- **Advanced Materials:** Continued research and development of new materials for pipeline construction and repair, with superior mechanical properties, increased durability and improved resistance to corrosion and other forms of degradation. Developing suitable materials for hydrogen transport is also an emerging priority.
- **Data Fusion and Visualization:** Developing more efficient platforms and techniques for fusing data from multiple and heterogeneous sources and creating intuitive and interactive visualizations that facilitate rapid understanding of integrity status and associated risks.
- **Sustainability and ESG (Environmental, Social, Governance) considerations:** Increased attention will be paid to reducing the environmental impact of pipeline operations, including minimizing leakage and emissions (related to product or maintenance activities), selecting materials and technologies with a low environmental footprint, and improving transparency and engagement with communities.
- **Cybersecurity:** As pipeline control and monitoring systems become increasingly digitalized and interconnected, protecting them against cyberattacks becomes an essential component of risk management.

The convergence of advanced digital technologies – AI/ML, IoT sensors, robotics and digital twins – heralds a new era in pipeline integrity management, often referred to as "Pipeline 4.0".

This paradigm promises a much more automated, real-time data-driven and fundamentally predictive management, with the potential to dramatically improve the safety, efficiency and reliability of operations.

However, achieving this vision requires overcoming significant barriers related to investments in technology and data infrastructure, developing standards for interoperability, ensuring cybersecurity and, perhaps most importantly, transforming the workforce skills to operate and manage these complex systems.

In addition to technological advancements, sustainability and environmental impact considerations are becoming increasingly influential factors in integrity management strategies.

Public and regulatory pressure, coupled with increased corporate awareness, is pushing the industry to adopt practices that not only ensure immediate safety, but also minimize the long-term environmental footprint.

This can influence the choice of inspection and repair technologies (favoring non-invasive or low-emission solutions), the selection of materials, and the prioritization of investments in leak detection and prevention.

Finally, despite all the technological innovations, the fundamental challenges of managing physical infrastructure, especially aging infrastructure, and ensuring rigorous quality control throughout the pipeline's lifecycle—from material selection and fabrication, to construction, operation, and, crucially, during repair activities—remain relevant.

Technology is a powerful tool, but it cannot replace sound engineering principles, meticulous quality assurance, and vigilant long-term asset management.

Recommendations for future research and industry adoption

To continue progress in the field of oil pipeline repair management, concerted efforts are needed in both research and industrial implementation:

● Priority research directions:

- Long-term validation of composite repair performance and durability under diverse operational conditions and development of models to predict their degradation.
- Improving the accuracy, robustness and interpretability of AI/ML models for predictive maintenance and complex defect characterization from inspection data.
- Developing and validating reliable and cost-effective NDT techniques for the detection and sizing of critical defects (e.g. SCC cracks, weld defects) in non-penetrable or hard-to-reach pipelines.
- Advancing robotic capabilities for complex repair tasks (e.g. precision welding, application of internal repairs in difficult conditions) and increasing their autonomy and reliability.
- Standardizing data formats from various inspection and monitoring technologies to facilitate multi-source integration and analysis.
- Researching new materials for pipelines and repairs, with a focus on durability, resistance to aggressive environments and compatibility with future fluids (e.g. hydrogen).

● **Recommendations for industry adoption**

- Accelerate the adoption and rigorous implementation of PSMS frameworks (API RP 1173) to strengthen safety culture and holistic risk management.

- Strategic investments in data management infrastructure and in developing internal analytical capabilities to harness the potential of integrity data.
- Wider adoption of quantitative risk assessment (QRA) and predictive maintenance strategies to optimize decisions and resources.
- Actively support standardization efforts for emerging technologies (robotics, AI in PIM) to facilitate their safe and efficient adoption.
- Encourage collaboration and exchange of best practices between operators, technology providers, research institutions and regulators.
- Prioritize workforce training and development programs to ensure the necessary skills in the use of new technologies and in analyzing complex data.

Concluding remarks

Pipeline repair management has evolved significantly from a reactive approach to a proactive, integrated and data-driven one.

Advances in inspection, monitoring and repair technologies, together with the development of increasingly sophisticated integrity and safety management frameworks (PIM and PSMS), have contributed to improving the safety and reliability of this critical infrastructure.

However, major challenges remain, particularly those related to managing aging infrastructure, detecting complex defects, managing massive data volumes and ensuring quality throughout the life cycle.

The future of the field is closely linked to continued technological innovation, especially through the integration of artificial intelligence, robotics and advanced monitoring, and to the widespread adoption of predictive and quantitative approaches in risk management.

Ensuring the long-term safety of pipelines requires a continuous commitment to research, development, standardization and implementation of best available practices.

Collaboration between all stakeholders – operators, suppliers, researchers and authorities – is essential to address complex challenges and capitalize on the opportunities offered by new technologies, thus guaranteeing the safe and responsible transport of vital energy resources.

Annex 1

The software runtime data are:

[14.84] Defect nou a aparut (ID: 1, Severitate: 10)

[15.00] Echipa 0 a inceput reparatia defectului 1 (Severitate: 10). Timp de asteptare: 0.16

[16.21] Defect nou a aparut (ID: 2, Severitate: 9)

[16.58] Defect nou a aparut (ID: 3, Severitate: 1)

[17.00] Echipa 1 a inceput reparatia defectului 2 (Severitate: 9). Timp de asteptare: 0.79

[17.00] Echipa 2 a inceput reparatia defectului 3 (Severitate: 1). Timp de asteptare: 0.42

[17.04] Defect nou a aparut (ID: 4, Severitate: 8)

[19.60] Defect nou a aparut (ID: 5, Severitate: 9)

[23.09] Echipa 0 a finalizat reparatia defectului 1. Durata reparatiei: 8.09

[23.09] Echipa 0 a inceput reparatia defectului 5 (Severitate: 9). Timp de asteptare: 3.49

[23.85] Defect nou a aparut (ID: 6, Severitate: 10)

[24.09] Defect nou a aparut (ID: 7, Severitate: 8)

[26.07] Defect nou a aparut (ID: 8, Severitate: 2)

[26.14] Echipa 2 a finalizat reparatia defectului 3. Durata reparatiei: 9.14

[26.14] Echipa 2 a inceput reparatia defectului 6 (Severitate: 10). Timp de asteptare: 2.28

[26.53] Echipa 2 a finalizat reparatia defectului 6. Durata reparatiei: 0.39

[26.53] Echipa 2 a inceput reparatia defectului 4 (Severitate: 8). Timp de asteptare: 9.49

[27.65] Defect nou a aparut (ID: 9, Severitate: 10)

[32.89] Defect nou a aparut (ID: 10, Severitate: 8)

[34.89] Echipa 0 a finalizat reparatia defectului 5. Durata reparatiei: 11.80

[34.89] Echipa 0 a inceput reparatia defectului 9 (Severitate: 10). Timp de asteptare: 7.24

[34.94] Echipa 1 a finalizat reparatia defectului 2. Durata reparatiei: 17.94

[34.94] Echipa 1 a inceput reparatia defectului 7 (Severitate: 8). Timp de asteptare: 10.84

[40.05] Defect nou a aparut (ID: 11, Severitate: 5)

[41.49] Echipa 2 a finalizat reparatia defectului 4. Durata reparatiei: 14.96

[41.49] Echipa 2 a inceput reparatia defectului 10 (Severitate: 8). Timp de asteptare: 8.60

[43.41] Defect nou a aparut (ID: 12, Severitate: 1)

[44.65] Defect nou a aparut (ID: 13, Severitate: 3)

[47.10] Echipa 2 a finalizat reparatia defectului 10. Durata reparatiei: 5.61

[47.10] Echipa 2 a inceput reparatia defectului 11 (Severitate: 5). Timp de asteptare: 7.04

[47.83] Echipa 1 a finalizat reparatia defectului 7. Durata reparatiei: 12.89

[47.83] Echipa 1 a inceput reparatia defectului 13 (Severitate: 3). Timp de asteptare: 3.18

[49.39] Defect nou a aparut (ID: 14, Severitate: 5)

[50.05] Defect nou a aparut (ID: 15, Severitate: 6)

[51.49] Defect nou a aparut (ID: 16, Severitate: 2)

[52.09] Defect nou a aparut (ID: 17, Severitate: 1)

[55.87] Defect nou a aparut (ID: 18, Severitate: 5)

[59.78] Echipa 2 a finalizat reparatia defectului 11. Durata reparatiei: 12.68

[59.78] Echipa 2 a inceput reparatia defectului 15 (Severitate: 6). Timp de asteptare: 9.73

[60.74] Echipa 2 a finalizat reparatia defectului 15. Durata reparatiei: 0.96

[60.74] Echipa 2 a inceput reparatia defectului 14 (Severitate: 5). Timp de asteptare: 11.35

[62.60] Defect nou a aparut (ID: 19, Severitate: 1)

[68.61] Echipa 2 a finalizat reparatia defectului 14. Durata reparatiei: 7.87

[68.61] Echipa 2 a inceput reparatia defectului 18 (Severitate: 5). Timp de asteptare: 12.74

[70.80] Echipa 2 a finalizat reparatia defectului 18. Durata reparatiei: 2.19

[70.80] Echipa 2 a inceput reparatia defectului 8 (Severitate: 2). Timp de asteptare: 44.72

[71.13] Echipa 0 a finalizat reparatia defectului 9. Durata reparatiei: 36.24

[71.13] Echipa 0 a inceput reparatia defectului 16 (Severitate: 2). Timp de asteptare: 19.64

[72.19] Echipa 0 a finalizat reparatia defectului 16. Durata reparatiei: 1.07

[72.19] Echipa 0 a inceput reparatia defectului 12 (Severitate: 1). Timp de asteptare: 28.79

[72.21] Echipa 2 a finalizat reparatia defectului 8. Durata reparatiei: 1.41

[72.21] Echipa 2 a inceput reparatia defectului 17 (Severitate: 1). Timp de asteptare: 20.12

[72.39] Echipa 1 a finalizat reparatia defectului 13. Durata reparatiei: 24.56

[72.39] Echipa 1 a inceput reparatia defectului 19 (Severitate: 1). Timp de asteptare: 9.78

[72.58] Defect nou a aparut (ID: 20, Severitate: 8)

[75.72] Echipa 0 a finalizat reparatia defectului 12. Durata reparatiei: 3.52

[75.72] Echipa 0 a inceput reparatia defectului 20 (Severitate: 8). Timp de asteptare: 3.13

[77.29] Echipa 2 a finalizat reparatia defectului 17. Durata reparatiei: 5.08

[80.10] Echipa 1 a finalizat reparatia defectului 19. Durata reparatiei: 7.72

[80.59] Defect nou a aparut (ID: 21, Severitate: 9)

[81.10] Echipa 1 a inceput reparatia defectului 21 (Severitate: 9). Timp de asteptare: 0.52

[81.95] Defect nou a aparut (ID: 22, Severitate: 10)

[82.29] Echipa 2 a inceput reparatia defectului 22 (Severitate: 10). Timp de asteptare: 0.34

[83.66] Echipa 0 a finalizat reparatia defectului 20. Durata reparatiei: 7.95

[86.60] Defect nou a aparut (ID: 23, Severitate: 10)

[86.66] Echipa 0 a inceput reparatia defectului 23 (Severitate: 10). Timp de asteptare: 0.06

[93.98] Echipa 2 a finalizat reparatia defectului 22. Durata reparatiei: 11.69

[94.09] Echipa 0 a finalizat reparatia defectului 23. Durata reparatiei: 7.43

[94.22] Defect nou a aparut (ID: 24, Severitate: 3)

[94.98] Echipa 2 a inceput reparatia defectului 24 (Severitate: 3). Timp de asteptare: 0.76

[100.87] Echipa 2 a finalizat reparatia defectului 24. Durata reparatiei: 5.89

[100.93] Defect nou a aparut (ID: 25, Severitate: 9)

[101.09] Echipa 0 a inceput reparatia defectului 25 (Severitate: 9). Timp de asteptare: 0.16

[102.34] Echipa 0 a finalizat reparatia defectului 25. Durata reparatiei: 1.25

[108.34] Defect nou a aparut (ID: 26, Severitate: 10)

[108.87] Echipa 2 a inceput reparatia defectului 26 (Severitate: 10). Timp de asteptare: 0.52

[109.95] Defect nou a aparut (ID: 27, Severitate: 1)

[110.34] Echipa 0 a inceput reparatia defectului 27 (Severitate: 1). Timp de asteptare: 0.38

[115.09] Defect nou a aparut (ID: 28, Severitate: 6)

[119.71] Defect nou a aparut (ID: 29, Severitate: 10)

[125.83] Echipa 2 a finalizat reparatia defectului 26. Durata reparatiei: 16.97

[125.83] Echipa 2 a inceput reparatia defectului 29 (Severitate: 10). Timp de asteptare: 6.13

[126.42] Defect nou a aparut (ID: 30, Severitate: 9)

[127.33] Echipa 2 a finalizat reparatia defectului 29. Durata reparatiei: 1.50

[127.33] Echipa 2 a inceput reparatia defectului 30 (Severitate: 9). Timp de asteptare: 0.91

[128.25] Defect nou a aparut (ID: 31, Severitate: 8)

[130.85] Defect nou a aparut (ID: 32, Severitate: 3)

[139.13] Echipa 2 a finalizat reparatia defectului 30. Durata reparatiei: 11.80

[139.13] Echipa 2 a inceput reparatia defectului 31 (Severitate: 8). Timp de asteptare: 10.88

[142.57] Defect nou a aparut (ID: 33, Severitate: 3)

[143.13] Defect nou a aparut (ID: 34, Severitate: 2)

[146.13] Echipa 1 a finalizat reparatia defectului 21. Durata reparatiei: 65.02

[146.13] Echipa 1 a inceput reparatia defectului 28 (Severitate: 6). Timp de asteptare: 31.04

[148.70] Defect nou a aparut (ID: 35, Severitate: 2)

[154.06] Echipa 0 a finalizat reparatia defectului 27. Durata reparatiei: 43.72

[154.06] Echipa 0 a inceput reparatia defectului 32 (Severitate: 3). Timp de asteptare: 23.21

[156.56] Defect nou a aparut (ID: 36, Severitate: 4)

[157.87] Defect nou a aparut (ID: 37, Severitate: 7)

[159.66] Defect nou a aparut (ID: 38, Severitate: 6)

[162.36] Echipa 1 a finalizat reparatia defectului 28. Durata reparatiei: 16.23

[162.36] Echipa 1 a inceput reparatia defectului 37 (Severitate: 7). Timp de asteptare: 4.49

[163.16] Echipa 2 a finalizat reparatia defectului 31. Durata reparatiei: 24.03

[163.16] Echipa 2 a inceput reparatia defectului 38 (Severitate: 6). Timp de asteptare: 3.50

[164.14] Echipa 2 a finalizat reparatia defectului 38. Durata reparatiei: 0.98

[164.14] Echipa 2 a inceput reparatia defectului 36 (Severitate: 4). Timp de asteptare: 7.58

[168.15] Echipa 1 a finalizat reparatia defectului 37. Durata reparatiei: 5.79

[168.15] Echipa 1 a inceput reparatia defectului 33 (Severitate: 3). Timp de asteptare: 25.58

[169.16] Defect nou a aparut (ID: 39, Severitate: 3)

[173.16] Echipa 1 a finalizat reparatia defectului 33. Durata reparatiei: 5.01

[173.16] Echipa 1 a inceput reparatia defectului 39 (Severitate: 3). Timp de asteptare: 4.00

[177.05] Echipa 1 a finalizat reparatia defectului 39. Durata reparatiei: 3.89

[177.05] Echipa 1 a inceput reparatia defectului 34 (Severitate: 2). Timp de asteptare: 33.92

[177.46] Defect nou a aparut (ID: 40, Severitate: 6)

[179.86] Defect nou a aparut (ID: 41, Severitate: 6)

[181.29] Defect nou a aparut (ID: 42, Severitate: 3)

[187.48] Echipa 2 a finalizat reparatia defectului 36. Durata reparatiei: 23.34

[187.48] Echipa 2 a inceput reparatia defectului 40 (Severitate: 6). Timp de asteptare: 10.02

[188.30] Echipa 2 a finalizat reparatia defectului 40. Durata reparatiei: 0.82

[188.30] Echipa 2 a inceput reparatia defectului 41 (Severitate: 6). Timp de asteptare: 8.44

[195.54] Echipa 2 a finalizat reparatia defectului 41. Durata reparatiei: 7.23

[195.54] Echipa 2 a inceput reparatia defectului 42 (Severitate: 3). Timp de asteptare: 14.25

[197.99] Defect nou a aparut (ID: 43, Severitate: 7)

Bibliography

1. R.Vladescu, Contribuţii la îmbunătățirea tehnologiilor de mentenanță a sistemelor de transport prin conducte a hidrocarburilor fluide în scopul creșterii gradului de siguranță în exploatare, Teză de doctorat (2022), https://www.upg-ploiesti.ro/sites/default/files/doctorat/VLADESCU%20ROBERT_ANUNTURI%20SUSTINERE%20TEZA%20DOCTORAT.pdf.
2. Z. Li, Y. Liang, Q. Liao, B. Zhang, H. Zhang, A review of multiproduct pipeline scheduling: from bibliometric analysis to research framework and future research directions, J. Pipeline Sci. Eng. 1 (2021) 395–406.
3. T. Chiș -Liquid Pipeline Accident Statistics Base for Pipeline Rehabilitation, International Pipeline Conference, Calgary, Canada, 9-14 June, 1996, Proceedings of the International Pipeline Conference, ASME, ISBN 079187679, New York, (1996) 6 pg, pg 319-327.
4. I. Ozturk, A literature survey on energy–growth nexus, Energy Pol. 38 (2010) 340–349.
5. M. Soltani, B. Hajipour, J. Tayebinia, Identifying the factors affecting competitiveness: a case study of Iranian natural gas industry, Energy Strategy Rev. 36 (2021).
6. T. Chis, R. Radulescu, D. Stoianovici, Vlădescu, R., A New Model of Oil Pipeline (Oleduct) Risk Assessment. International Journal of Safety & Security Engineering, (2021) 13(1).
7. R. G. Vlădescu, Problems in insuring maintenance of transport systems of fluid hydrocarbons through metal pipes, BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI Publicat de Universitatea Tehnică „Gheorghe Asachi" din Iaşi, (2021), Volumul 67 (71), Numărul 2, 2021 Secţia CONSTRUCŢII DE MAŞINI DOI:10.2478/bipcm-2021-0012.
8. G. Mutezo, J. Mulopo, A review of Africa's transition from fossil fuels to renewable energy using circular economy principles, Renew. Sustain. Energy Rev. 137 (2021).
9. https://www.tdwilliamson.com/company/who-we-are/history.
10. https://inspectioneering.com/journal/2017-04-27/6416/a-history-of-in-line-inspection-tools.
11. https://www.pipeliner.com.au/internationalnews/the-origin-of-intelligent-pigs/.
12. https://en.wikipedia.org/wiki/Pigging.

13. R. G. Vlădescu, Methods of carrying out the anticipative maintenance of fluid hydrocarbons transport systems. BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI Publicat de Universitatea Tehnică „Gheorghe Asachi” din Iaşi (2021), Volumul 67 (71), Numărul 3, 2021 Secţia CONSTRUCŢII DE MAŞINI DOI:10.2478/bipcm-2021-0016.
14. X.L. Gong, J.M. Liu, X. Xiong, W. Zhang, The dynamic effects of international oil price shocks on economic fluctuation, Resour. Pol. 74 (2021).
15. C. Chen, C. Li, G. Reniers, F. Yang, Safety and security of oil and gas pipeline transportation: a systematic analysis of research trends and future needs using WoS, J. Clean. Prod. 279 (2021).
16. A. Bazyar, N. Zarrinpoor, A. Safavian, Optimal design of a sustainable natural gas supply chain network under uncertainty, Chem. Eng. Res. Des. 176 (2021) 60–88.
17. F. Shaikh, Q. Ji, P.H. Shaikh, N.H. Mirjat, M.A. Uqaili, Forecasting China’s natural gas demand based on optimised nonlinear grey models, Energy 140 (2017) 941–951.
18. B. Wang, M. Yuan, H. Zhang, W. Zhao, Y. Liang, An MILP model for optimal design of multi-period natural gas transmission network, Chem. Eng. Res. Des. 129 (2018) 122–131.
19. H. Zhang, Y. Liang, Q. Liao, J. Chen, W. Zhang, Y. Long, C. Qian, Optimal design and operation for supply chain system of multi-state natural gas under uncertainties of demand and purchase price, Comput. Ind. Eng. 131 (2019) 115–130.
20. R.Vladescu, M.Banica, T. Chis, Explosion of the gas pipeline in Sighet-Romania, International Journal of Engineering, Management and Humanities (IJEMH), Volume 2, Issue 4, (2021), pp: 383-389 www.ijemh.com,
21. http://ijemh.com/issue_dcp/Explosion%20of%20the%20gas%20pipeline%20in%20Sighet%20Romania.pdf.
22. https://oilfieldafricareview.com/bg-technical-linalog-magnetic-flux-leakage-mfl-pipeline-intelligent-inspection-technology/.
23. https://en.wikipedia.org/wiki/List_of_countries_by_total_length_of_pipelines.
24. https://www.petroleumhistory.org/OilHistory/pages/Pipelines/first.html.
25. https://beltmag.com/uncovering-america-first-oil-landscape/.
26. https://www.okazii.ro/bustenari-sonde-a213270913.

27. Milwaukee Daily Sentinel [Milwaukee, Wisconsin] 21 Jan. 1874, and Gas Explosion in Bennington, Vt, Independent Statesman [Concord, New Hampshire], 22 Jan. 1874: 132, Gale NewsVault: Nineteenth Century U.S. Newspapers.
28. https://bjmures.ro/wp-content/uploads/2024/02/C00125.pdf.
29. Inspection and maintenance of oil & gas pipelines: a review of policies - ResearchGate, https://www.researchgate.net/publication/304041364_Inspection_and_maintenance_of_oil_gas_pipelines_a_review_of_policies.
30. Pipeline Integrity Management, accesată pe aprilie 30, 2025, https://pstrust.org/wp-content/uploads/2015/10/Kowalewski-IM-PE_Report.pdf.
31. Importance Of Pipeline Integrity Management - NWE, accesată pe aprilie 30, 2025, https://nwegroup.no/importance-of-pipeline-and-piping-integrity/.
32. Pipeline Integrity Regulations & Standards - AUCSC, accesată pe aprilie 30, 2025, https://aucsc.com/downloads/PIM_Pipeline%20Integrity%20and%20Standards_2019.pdf.
33. What is Pipeline Integrity? Procedures, Benefits and The Standards - PetroSync, accesată pe aprilie 30, 2025, https://www.petrosync.com/blog/what-is-pipeline-integrity/.
34. Pipeline Safety Management System (PSMS) - Unitil, accesată pe aprilie 30, 2025, https://unitil.com/energy-projects/pipeline-safety-management-system-psms.
35. Pipeline Risks - Tip of the Mitt Watershed Council, accesată pe aprilie 30, 2025, https://watershedcouncil.org/policy-advocacy/state/pipelines/pipeline-risks/.
36. Pipeline Integrity Management System | US - TUV Rheinland, accesată pe aprilie 30, 2025, https://www.tuv.com/usa/en/pipeline-integrity-management-system.html.
37. Accidents Waiting to Happen: Oil Pipelines - Frontier Group, accesată pe aprilie 30, 2025, https://frontiergroup.org/resources/accidents-waiting-to-happen-oil-pipelines/.
38. Q. Liao, Y. Liang, N. Xu, H. Zhang, J. Wang, X. Zhou, An MILP approach for detailed scheduling of multi-product pipeline in pressure control mode, Chem. Eng. Res. Des. 136 (2018) 620–637.
39. R. Avalos, T. Fitzgerald, R.R. Rucker, Measuring the effects of natural gas pipeline constraints on regional pricing and market integration, Energy Econ. 60 (2016) 217–231.

40. X. Zhou, Y. Liang, X. Zhang, Q. Liao, S. Gao, W. Zhang, H. Zhang, A MILP model for the detailed scheduling of multiproduct pipelines with the hydraulic constraints rigorously considered, Comput. Chem. Eng. 130 (2019).
41. C. Dieckhoner, S. Lochner, D. Lindenberger, European natural gas infrastructure: the impact of market developments on gas flows and physical market integration, Appl. Energy 102 (2013) 994–1003.
42. V.G. Cafaro, D.C. Cafaro, C.A. Mendez, J. Cerda, MINLP model for the detailed scheduling of refined products pipelines with flow rate dependent pumping costs, Comput. Chem. Eng. 72 (2015) 210–221.
43. T. Keller, G.H. Kuper, M. Mulder, Mergers of Germany's natural gas market areas: is transmission capacity booked efficiently? Util. Pol. 56 (2019) 104–119.
44. S.Nazari , H.A Kuzma, III, J.W. Rector, Predicting permeability from well log data and core measurements using support vector machines. In: SEG Technical Program Expanded Abstracts 2011. Society of Exploration Geophysicists, (2011), pp. 2004–2008.
45. S.O. Olatunji, A. Selamat, A. Abdulraheem, Modeling the permeability of carbonate reservoir using type-2 fuzzy logic systems. Comput. Ind. (2011), 62 (2), 147–163.
46. E. Oyewole, M. Saneifar, Z. Heidari, et al., Multi-scale characterization of pore structure in carbonate formations: application to the sacroc unit. In: SPWLA 56th Annual Logging Symposium. Society of Petrophysicists and Well-Log Analysts, (2015).
47. D. Potts, C. Sammut, Incremental learning of linear model trees. Mach. Learn. 61 (2005), (1–3), 5–48.
48. J.R. Quinlan, Learning with continuous classes. In: Proceedings of 5th Australian Joint Conference on Artificial Intelligence, vol. 92. (1992), pp. 343–348.
49. J. Raiga-Clemenceau, J. Martin, S. Nicoletis, et al., The concept of acoustic formation factor for more accurate porosity determination from sonic transit time data. In: Proceedings of the 27th SPWLA Annual Logging Symposium. Society of Petrophysicists and Well-Log Analysts, (1986).
50. B.D. Ripley, Pattern Recognition and Neural Networks. Cambridge University Press (2007).
51. J.J. Rodríguez, C. García-Osorio, J. Maudes, J.F. Díez-Pastor, An experimental study on ensembles of functional trees. In: International Workshop on Multiple Classifier Systems. Springer, (2010), pp. 64–73.

52. M. Saemi, M.Ahmadi, A.Y. Varjani, Design of neural networks using genetic algorithm for the permeability estimation of the reservoir. J. Petrol. Sci. Eng. (2007), 59 (1–2), 97–105.
53. C. Avraam, D. Chu, S. Siddiqui, Natural gas infrastructure development in North America under integrated markets, Energy Pol. 147 (2020).
54. E. Dukhanina, O. Massol, Spatial integration of natural gas markets: a literature review, Curr. Sustain./Renew. Energy Rep. 5 (2018) 129–137.
55. M.T. Devine, M. Russo, Liquefied natural gas and gas storage valuation: lessons from the integrated Irish and UK markets, Appl. Energy 238 (2019) 1389–1406.
56. E. Dukhanina, O. Massol, F. L´ evˆ eque, Policy measures targeting a more integrated gas market: impact of a merger of two trading zones on prices and arbitrage activity in France, Energy Pol. 132 (2019) 583–593.
57. X. Tong, J. Zheng, B. Fang, Strategic analysis on establishing a natural gas trading hub in China, Nat. Gas. Ind. B 1 (2014) 210–220.
58. A. del Valle, P. Duenas, S. Wogrin, J. Reneses, A fundamental analysis on the implementation and development of virtual natural gas hubs, Energy Econ. 67 (2017) 520–532.
59. Crude Oil Transport: Risks and Impacts - Green Choices, accesată pe aprilie 30, 2025, https://www.greenchoices.cornell.edu/resources/publications/transport/Crude_Oil_Transport.pdf
60. Environmental Impacts and its Concerns due to Accidents in Oil& Gas Pipelines around India-a Mini review, accesată pe aprilie 30, 2025, https://www.heraldopenaccess.us/openaccess/environmental-impacts-and-its-concerns-due-to-accidents-in-oil-gas-pipelines-around-india-a-mini-review
61. The Danger of the Pipelines and Trains that Serve Refineries | Sightline Institute, accesată pe aprilie 30, 2025, https://www.sightline.org/2021/10/27/the-danger-of-the-pipelines-and-trains-that-serve-refineries/
62. PHMSA Final Rule - Gas Pipeline Leak Detection and Repair, accesată pe aprilie 30, 2025, https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2025-01/PHMSA%20Final%20Rule%20-%20Gas%20Pipeline%20Leak%20Detection%20and%20Repair%20-%20As%20submitted.pdf
63. Operations & Maintenance Enforcement Guidance Part 195 Subpart F - Pipeline and Hazardous Materials Safety Administration, accesată pe aprilie 30, 2025,

https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/docs/regulatory-compliance/pipeline/enforcement/5781/o-m-enforcement-guidance-part-195-7-21-2017.pdf

64. US Department of Transportation Pipeline and Hazardous Materials Safety Administration, accesată pe aprilie 30, 2025, https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2025-01/Report%20to%20Congress%20-%20PHMSA%20FY%202021-2022%20Pipeline%20Safety%20R%26D%20Update%20Report.pdf
65. https://www.researchgate.net/publication/237551949_In-Line_Inspection_using_Combined_Technologies_-_Magnetic_Flux_Leakage_and_Ultrasonic_Testing_and_their_Advantages/figures?lo=1&utm_source=google&utm_medium=organic,
66. https://inosol.id/services-magnetic-flux-leakage-caliper-geometry-crack-detector-stress-concentration-detector-tfi-transverse-field-inspection-in-line-inspection-pipeline/magnetic-flux-leakage-mfl-transverse-field-inspection-tfi-inline-inspection-pipeline/
67. https://www.pipecaregroup.com/ultrasonic-inspection/,
68. https://www.americanpipelinesolutions.com/caliper-pigging
69. https://halfrepairsleeve.com/split-sleeve-clamp/,
70. https://www.exportersindia.com/product-detail/full-encirclement-steel-pipe-sleeve-4304588.htm,
71. https://www.dwt-pipetools.com/en/products/pipe-welding-tools/pipeline-leak-repair-clamp/,
72. https://www.kerrengineeredsales.com/blog/tdw-firsts-isolation-tools-in-action,
73. https://www.apiwebstore.org/standards/1173?utm_term=api%20rp%201173&utm_campaign=Webstore+-+International&utm_source=adwords&utm_medium=ppc&hsa_acc=4890137417&hsa_cam=20477134457&hsa_grp=178894350912&hsa_ad=747633324637&hsa_src=g&hsa_tgt=kwd-860356452610&hsa_kw=api%20rp%201173&hsa_mt=e&hsa_net=adwords&hsa_ver=3&gad_source=1&gad_campaignid=20477134457&gbraid=0AAAAACF6QdGOOvMgDKHjXumF0NRTHjb1S&gclid=CjwKCAjw-svEBhB6EiwAEzSdrhnmJcKd2XAMfl3LsIsPNhL1CqFtwTNdE1TE6aWBEBraXUWhwNa8-hoCKwsQAvD_BwE,

74. https://www.ibm.com/support/pages/downloading-ibm-spss-statistics-20.
75. https://geodacenter.github.io/
76. https://www.microsoft.com/ro-ro/microsoft-365/excel.
77. https://www.mapchart.net/.
78. H. Nalbant, M. O. Kayalica, G. Kayakutlu, G. Kaya, An analysis of the natural gas pricing in natural gas hubs: an evaluation for Turkey, Energy Syst. (2020) 1–25, https://doi.org/10.1007/s12667-020-00395-8.
79. H. Yang, P. You, C. Shang, Distributed planning of electricity and natural gas networks and energy hubs, Appl. Energy 282 (2021).
80. T. Jamasb, M. Pollitt, T. Triebs, Productivity and efficiency of US gas transmission companies: a European regulatory perspective, Energy Pol. 36 (2008) 3398–3412.
81. J.A. Hern´ andez Ibarabal, Natural gas infrastructure investment, regulation and ownership: the Australian case, Pol. Stud. 32 (2011) 231–242.
82. U.d.P. Alberto Cavaliere, The Liberalisation of Natural Gas Markets: Regulatory Reform and Competition Failures in Italy, 2007.
83. C.v. Hirschhausen, Infrastructure, regulation, investment and security of supply: a case study of the restructured US natural gas market, Util. Pol. 16 (2008) 1–10.
84. F. Gasmi, J.D. Oviedo, Investment in transport infrastructure, regulation, and gas–gas competition, Energy Econ. 32 (2010) 726–736.
85. C. Chaton, F. Gasmi, M.-L. Guillerminet, J.-D. Oviedo, Gas release and transport capacity investment as instruments to foster competition in gas markets, Energy Econ. 34 (2012) 1251–1258.
86. I. Opolska, The efficacy of liberalization and privatization in introducing competition into European natural gas markets, Util. Pol. 48 (2017) 12–21.
87. K. Talus, United States natural gas markets, contracts and risks: what lessons for the European Union and Asia-Pacific natural gas markets? Energy Pol. 74 (2014) 28–34.
88. C. Mos´ acula, J.P. Chaves-Avila, J. Reneses, Reviewing the design of natural gas network charges considering regulatory principles as guiding criteria in the context of the increasing interrelation of energy carriers, Energy Pol. 126 (2019) 545–557.
89. F. Cernoch, B. Danc´ ak, H. Koouskova, A. Leshchenko, P. Ocelík, J. Osicka, V. Sebek, T. Vlcek, V. Zapletalova, The Future of the Druzhba Pipeline as a Strategic Challenge for the Czech Republic and Poland, 2012.
90. O. Voytyuk, The gas sector of Ukraine: past and future, Wschodnioznawstwo 14 (2020) 207–232.

91. https://www.dreamstime.com/photos-images/oil-gas-pipeline-grinding.html .
92. https://nautiluslive.org/tech/rov-hercules.
93. J. Ayaburi, S. Sharma, M. Bazilian, Comparative analysis of selected African natural gas markets and related policies, Energy Sustain. Dev. 63 (2021) 67–77.
94. M. Hallack, M. Vazquez, European Union regulation of gas transmission services: challenges in the allocation of network resources through entry/exit schemes, Util. Pol. 25 (2013) 23–32.
95. M. Yuan, H. Zhang, B. Wang, R. Shen, Y. Long, Y. Liang, Future scenario of China's downstream oil supply chain: an energy, economy and environment analysis for impacts of pipeline network reform, J. Clean. Prod. 232 (2019) 1513–1528.
96. K. Mohlin, The U.S. Gas Pipeline Transportation Market: An Introductory Guide with Research Questions for the Energy Transition, IO: Regulation, 2021.
97. M. Vazquez, M. Hallack, Design of Auctions for Short-Term Allocation in Gas Markets Based on Virtual Hubs, 2012.
98. E. Çam, D. Lencz, Pricing short-term gas transmission capacity: a theoretical approach to understand the diverse effects of the multiplier system, Energy Econ. 95 (2021).
99. J. Xiao, C. Song, G. Zu, L. Lv, B. She, X. Zhang, Gas transmission capability curve of natural gas system: concept and steady-state model, J. Nat. Gas Sci. Eng. 87 (2021).
101. M. Ahammed, Probabilistic estimation of remaining life of a pipeline in the presence of active corrosion defects. Int. J. Pres. Ves. Pip., (1998). 75(4), 321–329.
102. C.Bersani, L.Citro, R. V.Gagliardi, R.Sacile, A. M. Tomasoni, Accident occurance evaluation in the pipeline transport dangerous goods. Chem. Eng. Trans., (2010) 19, 249–254.
103. M. Bertolini, N. Bevilacqua, Methodology and theory oil pipeline cause analysis a classification tree approach. J. Qual. Mainten. Eng., (2006). 12(2), 186–198.
104. L.Chao, M. Skibniewski, Fuzzy logic for evaluating alternative construction technology." J. Constr. Eng. Manage., (1998). 10.1061/(ASCE)0733-9364(1998)124:4(297), 297–304.
105. P. M. Davis, J. Dubois, F.Gambardella, Uhlig, F. Performance of European cross-country oil pipelines: Statistical summary of reported spillages in 2008 and since 1971." CONCAWE Oil Pipelines Management Group, Special Task Force, Brussels (2010).
106. A. W. Dawotola, P. H. A. J. M. VanGelder, J. K. Vrijling, Risk assessment of petroleum pipelines using a combined analytical hierarchy process—fault tree analysis

(AHP-FTA). Proc., 7th Int. Probabilistic Workshop, Dirk Proske Verlag, Delft, The Netherlands (2009).

107.M. Detyniecki, B. Moubeche, B. Bouchon-Meunier, On the paradoxical success of mamdani's minimum-based inference. Studies in Fuzziness and Soft Computing, Combining Experimentation and Theory, Vol. 271. Scientific Publishing Services, Springer, Chennai, India, (2012) 259–270.

108.P. K. Dey, A risk based model for inspection and maintenance of cross country petroleum pipelines. J. Qual. Mainten. Eng., (2001). 7(1), 25–43.

109. P. K. Dey, S. O. Ogunlana, S .Naksuksakul, Risk-based maintenance model for offshore oil and gas pipelines: A case study. J. Qual. Mainten. Eng., (2004). 10(3), 169–183.

110.I. Dikmen, M. Birgonul, S. Kiziltas, Prediction of organizational effectiveness in construction companies. J. Constr. Eng. Manage., (2005) 10.1061/(ASCE)0733-9364(2005)131:2(252), 252–261.

111.E. E. Elbeltagi, T. Hegazy,. A hybrid Ai-based system for site layout planning in construction." Comput. Aided Civ. Infrastruct. Eng., (2001) 16(2), 79–93.

112.G. S. Fishman, Monte Carlo: Concepts, algorithms, and applications, Springer, (1996).

113.G.Fu, Z.Kapelan, P. Reed"Reducing the complexity of multiobjective water distribution system optimization through global sensitivity analysis." J. Water Resour. Plann. Manage., 10.1061/ (ASCE)WR.1943-5452.0000171, (2012). 196–207.

114.R. Goodland, Oil and gas pipelines social and environmental impact assessment: State of the art." IAIA 2005 (2005), Conf., Robert Goodland, McLean, VA.

115.J. M. Hallen, F.Caleyo, J. L. Gonzalez, Probabilistic condition assessment of corroding pipelines in Mexico. Proc., 3rd Pan American Conf. for Nondestructive Testing (PANNDT), (2003), Curran Associates, Red Hook, NY.

116.A. S. Hanna, W. B. Lotfallah, A fuzzy logic approach to the selection of cranes, Autom. Constr., (1999). 8(5), 597–608.

117.E.Horstkotte, What is a fuzzy expert system? Togai InfraLogic, ⟨http://www.austinlinks.com/Fuzzy/expert-systems.html⟩, (2002).

118.G. J. Hwang, S. T. Huang, A new environment for developing fuzzy expert systems. J. Inform. Sci. Eng., (1999), 15(1), 53–69.

119.W. Karwowski, A.Mital, Potential applications of fuzzy sets in industrial safety engineering. Fuzzy Set Syst., 19(2), (1986). 105–120.

120.J. L. Kennedy, Oil and gas pipeline fundamentals, 2nd Ed., (1993), PennWell Publishing Company, Oklahoma.
121.K. B. Khatri, K.Vairavamoorthy, E. Akinyemi, "Framework for computing a performance index for urban infrastructure systems using a fuzzy set approach." J. Infrastruct. Syst., 10.1061/(ASCE)IS .1943-555X.0000062, (2011) 163–175.
122.S. X. Li, S. R. Yu, H. L. Zeng, J. H. Li, Liang, R, Predicting corrosion remaining life of underground pipelines with a mechanically based probabilistic model." J. Petrol. Sci. Eng., (2009). 65(3–4), 162–166.
123.P. Meesad, Quantitative measures of a fuzzy expert system. Final Rep. IEEE NNC Student Summer Research, Intelligent Systems and Control Laboratory, Electrical and Computer Engineering, Oklahoma State Univ., IEEE Computer Society, Washington, DC(2001).
124.G. A. Miller, The magical number seven, plus or minus two: some limits on our capacity for processing information." Psychol. Rev., 63(2), (1956).