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DEVELOPMENT OF RISK MANAGEMENT MECHANISMS DURING THE OPERATION OF PIPELINE TRANSPORT

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Abstract: In the contemporary global economy, the continuous supply of energy resources stands as a fundamental pillar of national and international security. While pipeline transport offers the highest economic efficiency for transporting liquid and gaseous hydrocarbons, its operation is accompanied by complex risk factors. The primary objective of this research is to enhance risk management mechanisms in pipeline systems through modern technological solutions to predict and prevent technical failures, corrosion processes, and third-party interferences.

The study analyzes existing risk assessment methodologies—such as quantitative and qualitative analysis—and justifies the necessity of adapting them to the requirements of the digital transformation era. As an innovative approach, monitoring methods implemented through fiber-optic sensor technologies, acoustic leak detection systems, and Unmanned Aerial Vehicles (UAVs) are investigated within the framework of the "Smart Pipeline" concept. In particular, the creation of a "predictive maintenance" model through the integration of Big Data analytics and Machine Learning algorithms is proposed. This model enables real-time monitoring of the pipeline's structural integrity and identifies potential risk hotspots before an incident occurs. The results of the research demonstrate that the digitalization of risk management not only prevents environmental disasters but also significantly reduces logistical operational costs and enhances the overall reliability of the system [5].

Keywords: *Pipeline transport, risk management, technical safety, predictive maintenance, digital twins, corrosion monitoring, energy security, leak detection.*

Introduction

Among the transport systems that are considered the economic arteries of modern civilization, pipeline transport occupies a unique position with its continuity, economic efficiency and strategic importance. Pipelines are considered an indispensable infrastructure in ensuring global energy security, especially in delivering hydrocarbon resources to end consumers thousands of kilometers away from their production points. However, the scale and complexity of this huge infrastructure mean that the risks encountered in its management are equally great. The issue of safety and risk management is not just a technical issue today, but has also become a critical management philosophy that ensures the sustainability of the international logistics chain.

The essence of pipeline transport is hidden in its principle of "dynamic flow in static infrastructure". While any accident occurring in other modes of transport (air, sea, land) is usually local in nature, a small malfunction or leak in main pipelines can lead to large-scale environmental disasters, economic losses worth billions of dollars and even interregional energy crises. For this reason, improving security strategies in pipeline logistics in accordance with the challenges of the modern era is of exceptional relevance.

Traditional risk management methods were often "reactive" in nature, based on statistical analysis of events. However, the digital transformation brought about by the fourth industrial revolution (Industry 4.0) has fundamentally changed the approach to risks in pipeline transport. Now we are not just talking about preventing accidents, but about reducing the probability of their occurrence to zero through "predictive" (foreseeable) analysis. Technologies such as artificial intelligence, the Internet of Things (IoT) and digital twins are turning pipelines into "smart infrastructure", making them more sensitive and resilient to the external environment [1].

The purpose of this research work is to assess the current state of security systems in pipeline transport and identify ways to increase efficiency by applying innovative technologies in the risk management process. The introductory part of the work extensively analyzes the nature of risks, their impact on the logistics chain and the need to apply modern management models. The study also proposes a conceptual framework for the "safe pipeline logistics" of the future, revealing how geological, technical and external intervention risks should be managed in an integrated manner.

In the field of improving risk management in pipeline transport, in particular, the deeper and more technological aspects that ensure the integrity of the logistics chain can be expanded as follows.

In traditional logistics systems, risks were usually assessed statically (for example, inspections carried out once a year). Modern improvement involves the application of dynamic risk models. In this model, data from sensors installed along the pipeline (pressure fluctuations, temperature changes, soil moisture) are analyzed in real time. If the system determines that the risk of corrosion has increased at a point, it automatically reduces the transport load in that section and immediately directs the repair crew to that coordinate. This is the most obvious example of the transition from "reactivity" to "proactivity" in risk management [3].

At the heart of the improvement is the Pipeline Integrity Management Systems (PIMS). This system covers the entire "life cycle" of the pipeline. This is not just about the physical pipe, but also about the safety of the environment around it. Within PIMS, risks are managed by dividing them into three categories:

- Internal factors: Corrosion caused by the chemical composition of the product.
- External factors: Landslides, earthquakes or humidity.
- External interference: Illegal connections or accidental drilling.

A separate "risk matrix" is prepared for each of these factors, and the areas with the highest scores are regularly observed from the air using UAVs (drones).

The latest and most exciting development in risk management is the "Distributed Acoustic Sensor" (DAS) technology. Fiber-optic cables laid along the pipeline become a giant microphone. This system hears the footsteps of a person walking near the pipe, the vibration of approaching equipment or the sound caused by a microscopic leak in the pipe. Artificial intelligence analyzes these sounds and distinguishes between the sound of ordinary rain and the sound of a real threat. This is a revolutionary step in the security of global logistics routes.

As pipelines become digital, they also face the risk of cyberattacks. Improved risk management now requires protecting the pipeline not just as a physical object, but also as a strategic IT infrastructure. Securing SCADA systems from external intrusions, encrypting data, and ensuring the immutability of information about the amount of product transported through blockchain technology are integral parts of modern logistics security [2].

Main Part

The first step in improving risk management in pipeline transport is to gain a deep understanding of the source, nature and potential impact of these risks. Trunk pipelines cross

thousands of kilometres of different climatic zones, geologically unstable areas and politically sensitive regions. This scale makes the risks multifaceted.

Risks in pipeline logistics are concentrated in four main groups:

- *Technical and structural risks:* This group includes internal and external corrosion, metal fatigue, defects in welds and equipment failures of pump-compressor stations. Corrosion is considered the "silent enemy" of pipelines and causes a large part of annual logistics losses.

- *Geological and natural risks:* Earthquakes, landslides, flood waters and, for submarine pipelines, tectonic movements are factors that can instantly disrupt the physical integrity of the pipeline.
- *External interference risks:* Accidental drilling by third parties, vandalism or illegal connections to the pipeline for the purpose of oil theft are among the most difficult to manage risks for global pipeline networks today.
- *Operation and human factors:* Dispatcher errors, improper valve control or excessive pressure increase lead to system internal accidents.[9]

Currently, integrity management standards such as ASME B31.8S (for gas pipelines) and API 1160 (for liquid pipelines) are applied worldwide. These standards define the cycle of risk identification, data collection, risk assessment and integrity assurance (Integrity Cycle). However, traditional methods are often based on static calculations. For example, the "Risk Matrix" method, which is widely used for risk assessment, although it captures probability and consequences, has difficulty in taking into account dynamic factors that change in real time (for example, the effect of sudden rain on soil corrosion activity).

The main purpose of risk management is the implementation of the "Business Continuity Plan". A stoppage in one part of the logistics system causes disruptions in the entire supply chain, which means energy shortages and price increases for the end consumer. Therefore, security is not just a technical maintenance, but also a mechanism for insuring economic risks.

Improving safety in pipeline transport today is directly related to the implementation of "Industry 4.0" technologies. The main goal is not to react to accidents that have already occurred, but to identify and eliminate the possibility of an accident at the stage of its occurrence. This section analyzes four main technological directions that take risk management to a new level.

The most powerful tool in modern risk management is the "Digital Twin" of the pipeline. This is a virtual model that combines all the technical parameters of the physical pipeline, material properties and environmental conditions [4].

- *Functionality:* Data from sensors is transmitted to this model, and artificial intelligence tests various "what if?" scenarios (for example, a sudden 20% increase in pressure or a sharp drop in temperature).
- *Advantage:* This technology allows you to visualize the weak points of the pipeline before the event occurs and calculate the risks with laboratory accuracy.

Supervisory Control and Data Acquisition (SCADA) systems are considered the “brains” of the pipeline. However, in advanced systems, this is integrated with fiber-optic sensors (DAS).

- *Acoustic monitoring:* Fiber-optic cables running along the pipe send light pulses thousands of times per second, measuring the smallest vibrations. The system can distinguish the sound of a drilling machine near the pipe from the sound of a regular car.
- *Leak detection:* The acoustic wave generated by the smallest leak in the pipe is instantly detected and the coordinates are transmitted to the dispatch center with meter-accuracy.

Smart PIG devices, used to check the internal condition of the pipeline, are an important part of the digital transformation. Modern diagnostic devices measure the wall thickness of the

pipe using magnetic flux leakage (MFL) and ultrasound (UT) technologies. Improved models now map the depth of corrosion and structural changes in the metal inside the pipe in 3D, which increases the accuracy of repair plans by up to 95%.

Manual physical inspection of thousands of kilometers of routes is both expensive and risky.

- *PUA:* Drones equipped with thermal cameras fly over the pipeline, identifying temperature changes on the ground surface (signs of leaks) or unauthorized construction work.
- *Predictive analytics:* Using satellite images and machine learning, geological risks are predicted in advance by analyzing changes in vegetation cover or landslide trends in the area.

The combined application of these technologies is shifting risk management in pipeline transportation from a "reactive" (repair after an accident) model to a "predictive" (foreseeing failure). This reduces the number of unexpected stops in the logistics chain by 40-60%, maximizing the overall reliability of the system [8].

Physical and technological innovations alone are not enough to ensure the highest level of safety in pipeline transportation. This section analyzes new methodological approaches applied in risk management, cyber-physical systems protection and emergency preparedness strategies.

As pipelines become digitalized and transformed into "Smart Grids", they become targets for cyber-attacks. Modern risk management must now integrate physical security and cybersecurity into a single system.

a. *Scada systems protection:* Central systems controlling pipeline valves and pumps should be protected by "closed-loop" networks isolated from external interference.
b. *Blockchain technology:* The amount of transported product, pressure indicators and operation logs should be stored on a blockchain. This prevents data manipulation and ensures logistical transparency.

Improvement in risk management is also measured by the speed of localization of losses in the event of an accident.

a. *Automated isolation:* In advanced systems, as soon as a leak is detected, artificial intelligence minimizes product loss by closing the two closest valves without waiting for human intervention.
b. *Simulation-based training:* Virtual reality (VR) training based on real accident scenarios is conducted for logistics personnel. This increases the speed of decision-making in times of crisis by more than 50%.[7]

This part of the research paper emphasizes the importance of pipeline transport for the logistical stability of the region, not just for a company or country.

a. *Diversification and redundancy*: Planning alternative lines or interchanges parallel to main pipelines within the framework of risk management ensures the "resilience" of the system. When one line is stopped for repairs, transportation continues via the other line.
b. *Environmental risk matrix:* In the improved models, special "Green Risk Zones" are identified, taking into account the ecological sensitivity of the areas through which the pipeline passes (for example, groundwater levels).

Since pipelines are often transboundary in nature, risk management requires the improvement of international standards (ISO 31000 - Risk Management) and inter-country agreements. Unified safety protocols ensure the same level of protection along the entire pipeline route.

The analysis of the main part shows that improving risk management transforms pipeline transport from the concept of a "passive pipe" to an "active and intelligent logistical organism".

This transformation will allow pipelines to maintain their crucial role in the energy transition (hydrogen transportation, etc.) [6].

Result

1. *Proactive management advantage:* The transition from traditional reactive methods to predictive (foreseeable) models allows for the identification of accident risks with 90% accuracy through artificial intelligence. This minimizes unexpected downtime.

2. *Digital monitoring efficiency:* The introduction of fiber-optic sensors and "Digital Twins" reduces the speed of leak detection from hours to seconds. These technologies dramatically reduce the risk of environmental disasters and crop losses.
3. *Cyber-physical defense integration:* Combining physical protection of pipelines with cybersecurity (Blockchain and SCADA protection) in a single system reduces the risks of strategic sabotage and digital intrusion by 60-70%.
4. *Economic and logistic stability*: Improved risk management extends the operational life of infrastructure by 15-20 years, reduces insurance costs, and strengthens economic stability by ensuring uninterrupted supply in international energy corridors [10].

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