# SENSITIVITY ANALYSIS OF RISK CHARACTERISTICS TO THE TYPE OF INITIAL INFORMATION BASED ON A PIPELINE MONITORING SYSTEM

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**Abstract**

*The aim of our research is to construct a risk tree, determine the main risks characteristics, find the most dangerous paths of the risk scenario development with respect to maximization of the failure probability criterion and analyze the sensitivity of results with respect to the shape of system components lifetime distributions and coefficient of variation. Our investigation is based on an example of the automated system for remote monitoring of underwater sections Dzhubga-Lazarevskoye-Sochi gas pipeline*.

**Keywords:** risk tree, reliability, risk event, sensitivity analysis, monitoring system

## I. Introduction

The preventive maintenance of equipment and predicting the operation risks of complex industrial systems is a key factor in ensuring the sustainability of the industry today. 82 % of companies have experienced unplanned downtime over the past three years. Analyst firm Aberdeen Research says that unplanned downtime can cost a company as much as $260,000 an hour. The problem of risks with application to industrial systems has recently received increased attention. Numerous studies are devoted to this both in printed publications [1, 2] and in Internet source [3].

The papers [4-7] propose a new approach to the investigation of risk phenomena. It contains the possibility to analyze and construct the most dangerous paths for the risk scenario development with respect to different criteria. Since the initial information about the emergence and development of a risk event and the damage it brings is usually very limited, it becomes important to analyze the sensitivity of risk characteristics to it. The proposed approach also allows to do this.

The aim of our paper is to present a risk tree based on an example of a real system of remote monitoring of underwater sections of the Dzhubga-Lazarevskoye-Sochi gas pipeline. The annual capacity of the gas pipeline is up to 3.78 billion cubic meters of gas. The approximate service time is 50 years. The total pipeline length is 171.6 km, the underwater part is about 90% of the total length [8]. The gas pipeline runs approximately 4.5 km from the waterfront. The sea depth reaches 80 m. The monitoring system evaluates the vertical position of the pipeline to identify places of insufficient backfilling, exposure, sagging, determines the condition of the anticorrosive insulation coating, classifies it as serviceable or requiring repair, or as marginal, that is, not allowing further operation. Monitoring is the basis for the safe operation of any complex system. Monitoring system failures can lead to serious risks of failure of the system itself, with possible catastrophic consequences.

We determine the most dangerous paths of the risk scenario development with respect to maximization of the failure probability criterion and analyze the sensitivity of results with respect to the shape of system components lifetime distributions and coefficient of variation. Although we limit ourselves to the analysis of the monitoring system, we are also ready for a deeper analysis of the entire pipeline system. However, this requires more detailed background information.

## II. The problem statement

Consider the underwater pipeline monitoring system represented at the figure 1.

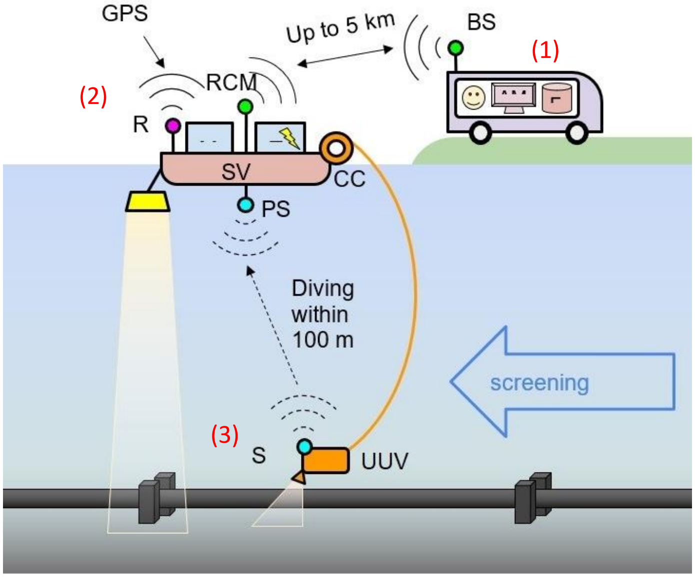


**Figure 1:** *The pipeline monitoring system*

Its hierarchical structure representation in the figure 2 with 3 main subsystems [1, 2, 9, 10]:
(1) – coast mobile operator center;
(2) – an accompanying surface vessel (SV), floating on the surface along the gas pipeline;
(3) –the remotely controlled unmanned underwater vehicle (UUV) "Vodyanoy-1".

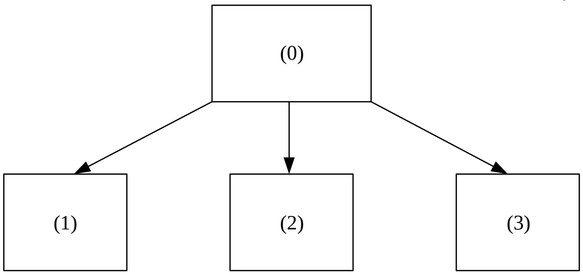


**Figure 2:** *A scheme of monitoring system*

Subsystems (1), (2) and (3) consist of lower-level subsystems.

The main segments associated with risky events for subsystem (1), are: (1,1) – control module/

operator's workplace; (1,1,1) – personal computer with a built–in DB; (1,1,2) – software analytics system; (1,1,3) – control tool/ joystick; (1,1,4) – radio system; (1,1,4,1) - network equipment; (1,1,4,2) –antenna; (1,2) – car.

In subsystem (2), the main elements that are significant in terms of the occurrence of risk events are: (2,1) – hydro echolocation system; (2,2) – control module; (2,2,1) – navigation system; (2,2,2) – local underwater positioning system; (2,2,3) – radio communication system; (2,2,4) – wire communication system for winch; (2,3) – power supply.

We define the following segments related to risk events in subsystem (3):

(3,1) – video system; (3,1,1) – camera; (3,1,2) – lamps; (3,2) – battery; (3,3) – tightness of the housing; (3,4) – control system; (3,5) – all sensors, such as a depth gauge, accelerometer, gyroscope; compass, voltage sensor; (3,6) – grab; (3,7) – motor drivers.

Based on expert assessments, we determine the initial information (the average service time) of the elements of the monitoring system in Table 1.

**Table 1:** *Initial information*

| Elements of subsystem (1) | Mean lifetime, years | Elements of subsystem (2) | Mean lifetime, years | Elements of subsystem (3) | Mean lifetime, years |
|---|---|---|---|---|---|
| (1,1,1) | 5 | (2,1) | 8 | (3,1,1) | 10 |
| (1,1,2) | 10 | (2,2,1) | 10 | (3,1,2) | 2 |
| (1,1,3) | 3 | (2,2,2) | 7 | (3,2) | 3 |
| (1,1,4,1) | 3 | (2,2,3) | 10 | (3,3) | 3 |
| (1,1,4,2) | 20 | (2,2,4,1) | 3 | (3,4) | 10 |
| (1,2) | 15 | (2,2,4,2) | 5 | (3,5) | 6 |
| | | (2,2,4,3) | 6 | (3,6) | 10 |
| | | (2,3) | 3 | (3,7) | 6 |

## III. Risk tree

According to the methodology proposed in [4, 5], a scheme of the monitoring system has been developed and a risk tree has been constructed, taking into account the possibilities for the risk scenario.

Vector $\vec{i} = (i_1, i_2, ..., i_r)$ denotes an element of the tree, its components determine the sequence of numbers of risk events, starting from the main subsystem and ending with the elementary one. Here $i_1$ is the number of the first level event from $k$ first level events. Then, $i_2$ - the number of the second level event that can be one of the reasons the uplevel event, etc, $r$ is a hierarchy level of this event. Designation $\vec{i}_k = \left(i_{k,1}, i_{k,2}, ..., i_{k,n(\vec{i}_k)}\right)$ is used for the $k$ level subsystem with the last element $n(\vec{i}_k)$, and $j$-th component of this subsystem is $j(\vec{i}_k)$. Let us divide the events into basic event (leaf) and other events. The round brackets for the leaf and square brackets for another event are used. For leaf events $A_{(\vec{i})}$ the average lifetime is given. The reliability of complex systems is investigated in terms of the reliability of elementary elements. Denote structural variable of an $i$-event by $x_i$, $1 \le i \le n$, $x_i$=1 if $i$-event occurs and $x_i$=0 otherwise. Corresponding structural function $\varphi(x_1, ..., x_n)$ can be calculated according to the rules of Boolean algebra, then $\varphi(x_1, ..., x_n) = 1$ if the system works, and $\varphi(x_1, ..., x_n) = 0$ otherwise [7].

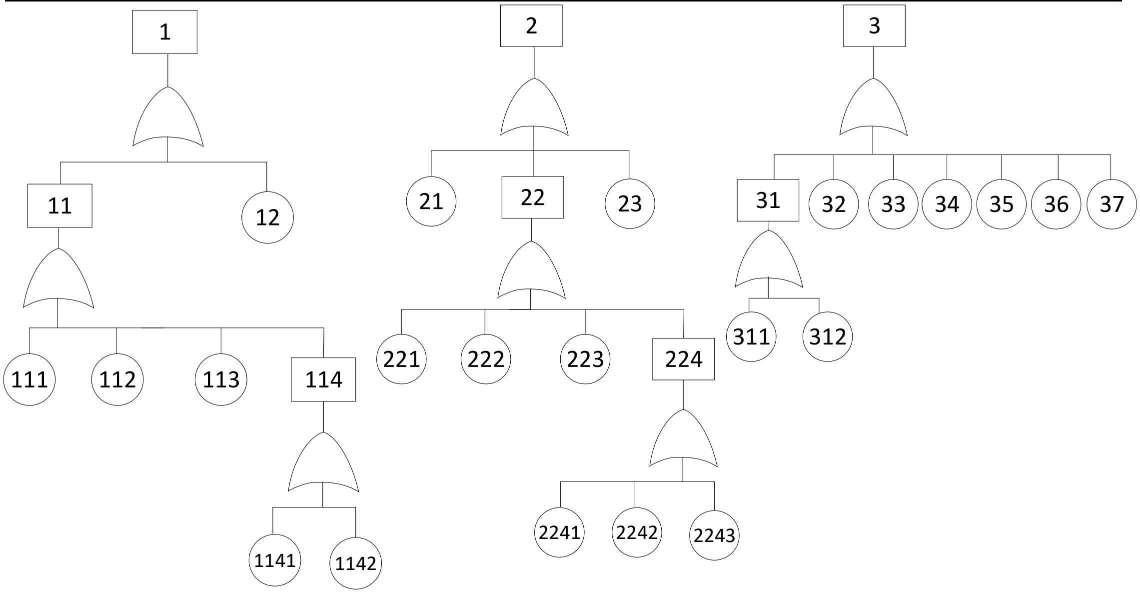


**Figure 3:** *Risk trees of subsystems (1), (2), (3).*

The main risk characteristics can be calculated with the help of structural functions, including the probability $q_{\vec{i}_k}(j)$ of $\vec{i}_k$ subsystem failure due to the failure of its $j$-component:

$$q_{\vec{i}_k}(j) = \int_0^\infty \left[ \prod_{\substack{i_k=1 \\ i_k \neq j}}^{n(\vec{i}_k)} R_{\overrightarrow{i_{k-1}}, i_k}(u) \right] dF_{\overrightarrow{i_{k-1}}, j}(u). \quad (1)$$

Using formula (2), we find the maximum failure probabilities $q^*_{\vec{i}_k}$ and the number of subsystem $j^*\left(\overrightarrow{i_k}\right)$ at which this maximum is reached.

$$q^*_{\vec{i}_k} = \max_{1 \le j \le n(\vec{i}_k)} q_{\vec{i}_k}(j); \qquad j^*_q\left(\overrightarrow{i_k}\right) = \arg\max_{1 \le j \le n(\vec{i}_k)} q_{\vec{i}_k}(j). \quad (2)$$

Collecting these values together, we find for any $k$ the most dangerous path according to the maximum failure probability criterion, including path for the entire system with $k = 1$:

$$\overrightarrow{i_k^*}(q) = j^*_q\left(\overrightarrow{i_k}\right), j^*_q\left(\overrightarrow{i^*_{k+1}}\right), \ldots, j^*_q\left(\overrightarrow{i^*_{r-1}}\right), \qquad \overrightarrow{i^*_{k+l+1}} = \left(\overrightarrow{i^*_{k+l}}, j^*\left(\overrightarrow{i^*_{k+l}}\right)\right). \quad (3)$$

Let us analyze the sensitivity of the risk parameters to the accuracy of the initial information for different lifetime distribution functions and three different values of coefficient of variation ($\nu = 0.5; 1; 2$).

## IV. Numerical experiment

In numerical experiments, we use Gnedenko-Weibull distribution (GW) and Gamma distribution (Gamma) for the lifetime distributions of the leaf elements.

The risk tree analysis consists in calculating the probabilities of a system failure and in determining the most dangerous paths of a risky situation according to the maximum failure probability criterion.

For the first experiment (I), we estimate the failure probability $q_0(j)$ of system (0) due to the failure of subsystems (1), (2) and (3), each leaf element has a coefficient of variation $v = 0.5$. The distribution functions at the lower levels are Gamma, at the next up level – GW, then again we take Gamma, etc. System failure is more likely due to subsystem (3), the greatest failure probability is given in bold. The results are shown in row I of the Table 2.

Fort the second experiment (II), we change the lifetime distribution function for one element (311) and calculate again probabilities $q_0(j)$, the other elements do not change. The initial data of the I and II experiments are close to each other, we can conclude that the replacement of the distribution function for one element has little effect on the subsystems failure probabilities. The subsystem (3) is also unreliable in this case, the results are presented in row 2 of the Table 2.

In the third experiment (III), element (311) has the same distribution function as in (I), but the coefficient of variation is $v = 2$, the other elements coincide with experiment (I). Subsystem (1) has the highest failure probability now. We conclude that the initial data characteristics can greatly influence the technological risks prediction and the construction of risk paths.

**Table 2:** *Estimated probabilities for the system*

| N | Description / Features | $q_0(1)$ | $q_0(2)$ | $q_0(3)$ |
|---|---|---|---|---|
| I | DF at the lower levels are Gamma, at the next up level GW, then again Gamma, $v = 0.5$ | 0.2374 | 0.2387 | **0.5239** |
| II | For one element (311), the lifetime distribution has been changed to GW | 0.2541 | 0.2334 | **0.5125** |
| III | For one element (311), the coefficient of variation has been changed $v = 2$ | **0.6537** | 0.1069 | 0.2394 |

## V. Conclusion and the further research

Numerical experiments have shown a slight sensitivity of the risk parameters to the type of lifetime distribution function of the system elements, but their significant sensitivity to the value of the coefficient of variation of these random variables. The work shows the importance of preparing and analyzing the initial information concerning the reliability parameters of system elements. The risk analysis methodology developed by the authors makes it possible to estimate not only the failure parameters, but also the damage parameters for the entire system and each subsystem. Unfortunately, the lack of information necessary for this analysis did not allow us to conduct research in this direction and include them in this work. We intend to continue research in this field and invite interested organizations and researchers with the necessary background information to support these studies.

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