UDC 004.81
DOI: 10.15587/1729-4061.2023.285862

A METHOD FOR IMPORTANCE AND RISK ASSESSMENT OF MAIN PIPELINE FACILITIES

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The issues of creating a method for solving a multi-criteria task of the importance and risk (hazard) assessment of trunk pipeline objects (sections) are considered. The method is developed on the basis of the analytic hierarchy process. Each object (section) of trunk pipelines is characterized by a set of particular criteria that have their own scale of possible values of different physical nature and different dominance in determining the overall object importance. In this regard, there is a problem of transition from estimates by physical parameters to dimensionless assessment using some membership function. The study proposes an approach to automating the process of assessing objects by particular parameters in the analytic hierarchy process. For this purpose, a method is proposed that allows experts to be excluded from the process of filling in the paired comparison matrix based on the formation of a system of rules. Having a vector of criteria importance and guided by a system of rules, it is enough to specify the actual values of criteria for each alternative to compare objects. Based on this method, a model has been developed that allowed experimental studies to be carried out in the developed software. This method, as well as the developed importance assessment and decision-making software, is used in the automated system of electrochemical protection of main pipelines. The results of evaluating the importance of criteria for the task of risk assessment of gas pipeline sections are presented. The results obtained and their practical implementation in the management of main gas pipelines confirmed the effectiveness of the developed method. This allows you to make decisions in situations where it is necessary to carry out a multi-criteria selection of currently effective solutions and management strategies, assess risks, prioritize elements and coordinate actions for modernization or development

Keywords: pipeline system, object importance assessment, analytic hierarchy process, membership function

Received date 19.05.2023
Accepted date 31.07.2023
Published date 31.08.2023

How to Cite: *Prokhorov, O., Prokhorov, V., Tevyashev, A., Khussanov, A., Khussanov, Z., Turdybekova, D. (2023). A method for importance and risk assessment of main pipeline facilities. Eastern-European Journal of Enterprise Technologies, 4 (3 (124)), 33–44. doi: https://doi.org/10.15587/1729-4061.2023.285862*

1. Introduction

In order to increase the efficiency of managerial decision-making on pipeline system (PLS) facilities or, in particular, main pipelines (MPL) during their operation, an assessment of their importance and risks (hazards) is required. The severity of the consequences of pipeline accidents and the variety of causes of failures emphasize how important it is to manage pipeline risks [1].

Common risk assessment methods include expert assessment, analytic hierarchy process, fuzzy integrated assessment, failure tree analysis, support vector machine, technique for order of preference by similarity to ideal solution (TOPSIS) and others. At the same time, there are issues of forming classes of objects being compared, determining the composition of significant properties for comparative assessment of objects among themselves and determining vectors of importance of properties and importance (priority) or risks (hazards) of compared objects.

PLS are characterized by functional and structural complexity, and the variety of tasks and goals to be solved. All this is a serious obstacle to obtaining analytical expressions that allow determining the priority of each of the compared system objects, especially in conditions of uncertainty. This makes it necessary to use the judgments of specialists (experts) in determining the priority of individual physical and informational properties of objects.

Rational use of information received from experts is possible when it is transformed into a form convenient for further analysis and making a final decision on the priorities of objects that can be characterized by some importance w_i. Then a certain vector of importance or priorities $W=\{w_i\}$ is assigned to the compared objects. As a rule, expert judgments are presented as numerical values selected on a certain scale. If an expert can compare and evaluate possible options by assigning a certain number to each of them, then it can be assumed that he has a certain preference system. Thus, mathematical and statistical methods of expert assessments (paired comparisons, sequential comparisons, direct evaluation, ranking, etc.) use numerical estimates.

So, research in the field of control and risk assessment of the pipeline system, identification and comparison of relative priorities of critical factors, determining the importance of main pipeline facilities, timely identification of potential hazards and threats, comparison of the overall effectiveness of solutions when choosing measures to prevent pipeline accidents, risk reduction, modernization and development are relevant.

2. Analysis of recent research and publications

The analytic hierarchy process (AHP) method is widely used in decision-making and involves evaluating expert judgments on an ordinal scale [2]. Here, the problem of forming a generalized criterion is calculated using importance estimates of objects based on estimates of the values of particular criteria. The analytic hierarchy process method includes procedures for the synthesis of multiple judgments, obtaining priority of criteria and finding alternative solutions. However, despite the wide scope of application, AHP has problems that complicate the process of its use. Therefore, this method is widely used and combined with other methods to solve problems, and also has various modifications.

One of the common combinations is the use of AHP and TOPSIS. It assumes that the chosen alternative should have the shortest distance from the ideal solution and the greatest distance from the anti-ideal solution. The risk assessment model of oil and gas pipelines based on modified AHP and TOPSIS is considered in the research work [3]. However, the system of criteria for risk assessment of oil and gas pipelines does not take into account such parameters as, for example, the proximity of settlements or industrial facilities, as well as environmental impact in case of possible accidents.

Fuzzy AHP (FAHP) is an extension of AHP by modeling subjective paired comparisons with fuzzy sets to account for their uncertainty [4]. Fuzzy TOPSIS (FTOPSIS) is a modification of TOPSIS to accept priorities or performance with fuzzy values [5]. At the same time, it should be taken into account that the calculation of the ratio between the indicators with the best and worst assessment levels may lead to a certain error in the final evaluation results. Also, the key point for this approach is the complexity in calculating the weights of evaluation criteria.

The research work [6] presents a simplified method based on AHP, which is associated with the selection of a noticeable alternative. It is based on the hypothesis that inconsistency arises mainly in estimates between alternatives that are insignificant to the decision-maker. However, the study lacks estimates of computational complexity when using a multi-level (three or more levels) goal system.

Many studies have been carried out on risk assessment in pipeline transport. A sufficient part of research is related to the use of methods that require accurate values for calculations and in the practical application of such approaches, in the absence of representative data and uncertainty factors, there are many difficulties and limitations. Therefore, another part of the researchers used methods based on expert decision-making to reduce the degree of uncertainty and increase the practical applicability of risk assessment results.

In [7], the problem of corrosion risk assessment for a gas pipeline is considered with determining the importance of indicators based on an improved analytic hierarchy process and fuzzy complex assessment. The limited number of indicators and their narrow focus on the forecast of corrosion damage to the pipeline does not make it possible to talk about a comprehensive solution to the problem of improving the safety of the pipeline system.

The study [8] proposes a three-stage method for assessing the safety of gas pipeline sections in China during modernization. The method is based on a quantitative risk assessment based on normative documents and regulations with the calculation of various parameters, such as the probability of failures by the boundary state method, the maximum allowable operating pressure, and others. This approach requires accurate numerical data for calculations and is quite difficult in practical application.

The study [9] proposes a method for assessing the risks of gas pipelines based on the bow-tie analysis and calculating the probability of failures based on fuzzy sets. It should be taken into account that the method can become quite cumbersome and complex and does not quantify the risk.

A method for assessing the reliability of a gas pipeline network based on the theory of complex networks and taking into account operational characteristics under the conditions of structural changes in the pipeline network is proposed in [10]. The approach assumes the availability of statistical data on the operation of the pipeline system and is mainly focused on assessing the reliability of the pipeline network with an increase in the degree of damage and accidents.

Risk assessment for oil and gas pipelines is considered in [11], which proposes to use a quantitative risk assessment based on the theory of set pair analysis. To determine the weight coefficients of the assessment criteria, the work presents a calculation method based on fuzzy set theory. However, the accuracy of the evaluation method strongly depends on the availability of relevant evaluation information, and this is not always possible in practice.

The study [12] devoted to the analysis of vulnerability concepts for assessing the safety status of pipeline systems emphasizes that a frequently used method for determining the importance of criteria in risk assessment problems in pipeline transport is the analytic hierarchy process. The authors emphasize the need for further improvement of scoring models, but do not offer anything new.

In [13], the analytic hierarchy process is used to calculate weights of criteria in assessing the safety of an urban gas pipeline system, and then a comprehensive assessment of the gas pipeline network is performed using a combination of the Failure, Modes, Effect and Criticality Analysis method and fuzzy complex analysis (FMECA-fuzzy).

In [14], a combination of the analytic hierarchy process and fuzzy complex assessment (AHM-FCE) methods is also used to assess the risk of maintenance and repair work on pipeline transport associated with the use of open fire.

To study uncertain factors in the process of risk assessment of gas pipelines, the work [15] proposes a three-level index system using the unascertained measure theory, where the weight of the assessment factors was determined using the analytic hierarchy process.

The analysis showed that most of the researchers who use the analytic hierarchy process focused on simplifying the traditional assessment scale and reducing the human subjective factor by switching to fuzzy estimates. However, such combinations are more aimed at increasing the applicability of the method in conditions of uncertainty than at solving the problems of increasing its practical feasibility, to which this study is devoted.

3. The aim and objectives of the study

The aim of the study is to develop a method for solving the multi-criteria task of assessing the importance and risks of PLS facilities, taking into account the automation of the process of evaluating objects by individual parameters in the AHP method.

To achieve the aim, the following objectives should be accomplished:

– to move from evaluating objects by physical parameters to dimensionless assessment;

– to formalize the process of making expert judgments on the assessment of object importance in the form of a system of rules;

– to conduct experiments on the use of the method in the risk assessment of PLS sites.

4. Materials and methods

The object of the study is decision support systems for improving the safety of pipeline transport. It should be noted that it is difficult to obtain analytical expressions to determine the priority of compared objects or solutions in conditions of the functional and structural complexity of PLS, as well as uncertainty.

The hypothesis of the research is to increase the practical feasibility of subjective measurement methods and the effectiveness of decision-making in multi-criteria tasks in pipeline transport. To assess the importance of the elements, the AHP method was used, based on a comparative assessment of expert judgments on a scale of preferences about the objects being compared. In the method proposed in this paper, experts can speak on the quality scale, and the system will automatically select the appropriate quantitative value (membership function) to form the appropriate value on the scale of relative importance for paired comparison matrices. In AHP, the expert does it himself, which leads to the problem of inconsistency, from the direct filling of which the expert is excluded in the proposed approach.

When objects are evaluated not by one, but by several features, properties or indicators, the complexity of analyzing and processing the results of examinations increases significantly. It becomes more time-consuming to determine their comparative preference. To do this, you need to know what factors and to what extent affect the evaluation of objects.

The problem arises of forming a generalized criterion, which allows calculating estimates of the importance of objects based on estimates of the values of particular criteria.

For this purpose, the decomposition of the problem (object) into simpler and simpler components and further processing of the sequence of expert judgments according to paired comparisons are carried out. These judgments are then expressed numerically. The values obtained in this way are estimates in the scale of relations.

The method, as well as the developed importance assessment and decision-making software, is used in the automated electrochemical protection system of main pipelines.

5. Results of the development of a method for assessing the importance and risks of main pipeline facilities

5. 1. Transition from object evaluation by physical parameters to dimensionless evaluation

Let experts consider objects $x_1, ..., x_n$, $x_i \in X$, a comparative assessment of the effectiveness (importance) of which is characterized by m ($m>1$) particular criteria $P_1, ..., P_m$, an m-dimensional assessment of the importance of each object w_i, $i\in\{i, ..., n\}$ can be represented by vector $W_i=(w_{i1}, ..., w_{im})$. Object x_1 is no less efficient than object x_2 ($x_1 \geq x_2$), if $W_1 \geq W_2$, i.e. $w_{1v} \geq w_{2v}$, $v\in\{1, ..., m\}$. It is assumed that the higher the effectiveness estimate of an object by a particular criterion, the more preferable the object according to this criterion. Object x_1 is more efficient than object x_2 ($x_1 \geq x_2$), if $W_1 > W_2$, i.e. $w_{1v} \geq w_{2v}$, and at least for one v $w_{1v} > w_{2v}$.

Another method of comparative assessment of multi-criteria alternatives (objects) in practical research is the method of generalized linear criteria [16], which assumes the search for weight coefficients $\lambda_1, ..., \lambda_m$, containing more information about the comparative importance (significance) of criteria $P_1, ..., P_m$, $W_i=(w_{i1}, ..., w_{im})$, than measurement in the order scale.

The measurability of importance estimates of particular criteria in a scale or in a quasi-scale of relations makes the procedure for comparative assessment of multi-criteria alternatives (objects) correct using a generalized linear criterion $\sum_{v=1}^{m}\lambda_v P_v(x_i)$. This criterion allows determining a linear order relation on a set of multi-criteria alternatives, which is one of the ways to solve the selection problem. The best alternative is x_{io}, for which:

$$\sum_{v=1}^{m}\lambda_v P_v(x_{io}) \geq \sum_{v=1}^{m}\lambda_v P_v(x_i), i\in\{1,...,n\}. \tag{1}$$

If it is necessary to choose k best alternatives, then these will be k alternatives that received the highest scores by criterion (1).

Based on the foregoing, it is possible to formulate the problem of expert assessment of MPL facilities (sites) in terms of importance.

The decomposition principle of the analytic hierarchy process provides for the structuring of this task in the form of a hierarchy or levels:

1) PLS management tasks for which objects are evaluated by importance;

2) criteria by which objects are compared.

Each PLS object can be characterized by a set of particular criteria (parameters, properties, performance characteristics, etc.), the list of which is considered to be given. Depending on the goals and objectives set, on the selected management strategies, from the entire set of particular criteria $P=\{P_1, ..., P_m\}$, when solving the problem of assessing the importance of alternatives, a subset $P_z \subset P$ is selected, which includes the criteria that are most relevant to the current situation.

Each criterion that characterizes the PLS object has its own scale of possible values. In each of them, it can have one or another value of importance. In addition, depending on the current situation, on the tasks being solved, one or another particular criterion from the subset P_z can have its own scale of priorities (importance) and thus dominate in determining the overall value of the object's importance.

In this regard, there is a task of transition from assessment by physical parameters to dimensionless assessment.

Let PLS solve k tasks. Various situations can also be considered as tasks. Then the importance values of the tasks are determined by experts and written as a vector: $Z=[z_1, ..., z_k]$, and the condition $\sum_{i=1}^{k} z_i = 1$ must be met.

Identification (definition) of a specific task (situation) is made according to a number of characteristic features $Q=\{Q_1, ..., Q_r\}$. A set of features Q should be necessary and sufficient for unambiguous identification of a particular task (situation).

Depending on the tasks to be solved, each property (parameter) of an object acquires a certain significance. The value of significance is determined by an expert and characterizes the importance (priority) of the object parameter when performing the task (for example, distribution of requests for service by devices). The values of the weight coefficients of the importance of the object parameters are given in the form of a matrix:

$$\Lambda = \begin{vmatrix} \lambda_{11} & \lambda_{12} & \dots & \lambda_{1m} \\ \lambda_{21} & \lambda_{22} & \dots & \lambda_{2m} \\ \dots & \dots & \dots & \dots \\ \lambda_{k1} & \lambda_{k2} & \dots & \lambda_{km} \end{vmatrix}, \qquad (2)$$

where λ_{ij}, $(i=1, ..., k; j=1, ..., m)$, matrix elements characterizing the importance of the j-th parameter (property) of an object when performing the i-th task, at the same time $\sum_{j=1}^{m} \lambda_{ij} = 1.$ Then we get the following priority vector:

$$W^{PR} = Z \cdot \Lambda = \left[W_1^{PR}, W_2^{PR}, ..., W_m^{PR}\right], \qquad (3)$$

which takes into account both the importance of tasks and the importance of object parameters.

The number of objects n is assumed to be finite and rather small so they can be enumerated directly. Partial estimates of objects for each parameter should take values in easily identifiable sets. Each of the P_j parameters (time, distance, volume, etc.) has a dimension. And the importance of the i-th object according to the j-th parameter is a dimensionless value $0<w_{ij}\leq 1$ and normalized, i.e. $\sum_{i=1}^{n} w_{ij} = 1.$

In this regard, there is a task of transition from assessment by physical parameters to dimensionless assessment. It should be noted that AHP can work with quantitative and qualitative indicators of objects and at the same time, like any other method of expert assessments, makes the transition to a dimensionless scale of assessment. In the case of AHP, it is a scale of relative importance from 0 to 9, which is used by experts when filling in paired comparison matrices. However, in order to reduce the influence of subjectivity, automate and further exclude experts from the process of filling in comparison matrices, an approach based on the preference function is proposed. Let us consider this method.

Let y_j be some dimensionless scale, according to which objects are evaluated by the P_j, parameter, and $y_j = f_{P_j}\left(P_j\right)$ is some function of mapping the values of the P_j parameter into the values of the y_j scale. Then the values of expert estimates can be obtained using some membership function $G=f_G(y)$. The membership function f_G in this case plays the role of a normalized utility function. The definition of the membership function is based on the presence of a preference relation between elements of a basic set.

The f_G estimate cannot be accurate. However, the selection of the curve shape allows expressing individual features of the decision-maker preferences. To reveal these individual features, one should not require him to express his preferences in the interval [0, 1] (the choice of which is quite arbitrary). It is more convenient to build a discrete preference scale containing 5–7 levels depending on the perception threshold of an expert. The easiest way is to express linguistically the levels of compatibility between the assessment and the goal of displaying these levels on a universal set [0, 1].

Fig. 1 shows the view of the membership function on a universal scale of values of the assessment quantifier. As an example, the Harrington function $f_G\left(y\right)=e^{-e^{-y}}$ is used [17].

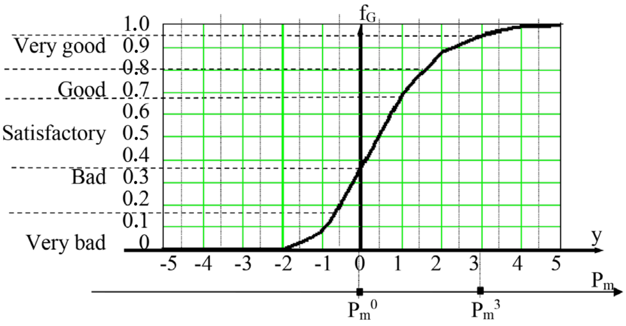


Fig. 1. Membership function $f_G\left(y\right)=e^{-e^{-y}}$

As is known, the Harrington function under one-sided constraints is calculated either by selecting control points using a first-stage polynomial or by simplified formulas. However, simplified expressions for calculation have significant drawbacks with both unilateral and bilateral constraints. In addition, the accuracy of establishing compliance for the beginning of the «good» sub-range is questionable, since this is some intermediate value and its definition depends entirely on the expert's opinion. Therefore, the goal of subsequent transformations is to eliminate the restriction of existing expressions for calculating the Harrington function and to eliminate the human factor in the evaluation process as much as possible.

5. 2. Formalization of the process of evaluating objects by particular parameters in the analytic hierarchy process

To automate the process of assessing objects by particular parameters, the following method is proposed.

Along the y abscissa axis (Fig. 1), the values of the estimated parameters relative to the P_m axis are combined. The ideal values of the object's parameters are taken, then the value of the P_m^0, parameter, which the expert considers to be the point between the «bad» and «satisfactory» ratings, is combined with the origin of coordinates $y=0$. The value P_m^3, corresponding to the «very good» rating is combined with $y=3$. The scale factor K_m is determined by the formula:

$$K_m = \left(P_m^0 - P_m^3\right) \cdot 3^{-1}. \qquad (4)$$

To evaluate the *i*-th object by the parameter P_m, which has the current value P_{mi}, y_{mi} is first calculated by the formula:

$$y_{mi} = \left(P_m^0 - P_{mi}\right) \cdot K_m^{-1}. \tag{5}$$

Then, according to the y_{mi} value, the value of the membership function $f_G(y_{mi})$ and the corresponding value of the estimate G_{mi} according to Table 1 are determined.

Table 1

Table for determining G_{mi} estimate values

G estimate	Range of *y* values	$f_G(y)$ values	Linguistic estimate
1	[–3; –0.5]	0; 0.192	Very bad
2	[–0.5; 0]	0.192; 0.368	Bad
3	[0; 1]	0.368; 0.692	Satisfactory
4	[1; 1.5]	0.692; 0.8	Good
5	[1.5; 3]	0.8; 0.95	Very good

It is clear that each physical parameter will have its own shape of the graph of the membership function. For example, the scale of soil corrosiveness, which, in turn, affects the risk of a particular site when assessing geological features along the pipeline route. It has the following intervals depending on soil resistivity (Ohm*m): 0–5 – extremely dangerous; 5–10 – very dangerous; 10–20 – dangerous; 20–50 – moderately dangerous; more than 50 – non-dangerous.

Thus, each object x_i receives an expert estimate G_{mi} for the selected P_m parameter. Then, using special rules for comparing two objects (7), square paired comparison matrices A_m are formed for each *m* parameter for all *n* objects:

$$A_m = \left|a_{ij}\right| = \begin{vmatrix} 1 & a_{12} & \dots & a_{1n} \\ a_{21} & 1 & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & 1 \end{vmatrix}. \tag{6}$$

This matrix has the properties of inverse symmetry, i.e. $a_{ij}=1$, at $i=j$, where *i* is the row number, *j* is the column number and $a_{ij}=1/a_{ji}$.

To form a paired comparison matrix for the selected parameter, the values of the expert assessment of the parameter are analyzed based on the scale of relative importance, which is presented in Table 2.

Using the comparison rules listed below, the elements of the matrix A_m are determined:

P1. If the object estimates $G_{mi}=G_{mj}$ by the parameter P_m, then $a_{ij}=a_{ji}=1$.

P2. If $G_{mi} - G_{mj} = 1$, then $a_{ij} = 3, a_{ji} = 1/3$.

P3. If $G_{mi} - G_{mj} = -1$, then $a_{ij} = 1/3, a_{ji} = 3$.

P4. If $G_{mi} - G_{mj} = 2$, then $a_{ij} = 5, a_{ji} = 1/5$.

P5. If $G_{mi} - G_{mj} = -2$, then $a_{ij} = 1/5, a_{ji} = 5$.

P6. If $G_{mi} - G_{mj} = 3$, then $a_{ij} = 7, a_{ji} = 1/7$. (7)

P7. If $G_{mi} - G_{mj} = -3$, then $a_{ij} = 1/7, a_{ji} = 7$.

P8. If $G_{mi} - G_{mj} = 4$, then $a_{ij} = 9, a_{ji} = 1/9$.

P9. If $G_{mi} - G_{mj} = -4$, then $a_{ij} = 1/9, a_{ji} = 9$.

P10. If $i = j$, then $a_{ij} = a_{ji} = 1$.

Table 2

Scale of relative importance

Relative importance	Definition
0	Objects are incomparable
1	Equal importance values
3	Moderate superiority
5	Substantial superiority
7	Strong superiority
9	Absolute superiority
2, 4, 6, 8	Intermediate judgments
Inverse numbers	Values in reverse comparison

In order to exclude experts from the process of filling in the matrix A_m, it is necessary to formalize the process of developing expert judgments on assessing the importance of objects. To do this, the results of the experts' activities can be represented in the form of certain rules (axioms). To form a paired comparison matrix for the selected parameter, the values of the expert assessment of the parameter are analyzed based on the scale of relative importance, which is presented in Table 2.

To determine the priority value of objects for each parameter, two operations are performed:

1. Normalization by the columns of the matrix A_m to obtain the matrix A_m^{norm}, each element a_{ij}^{norm} of which is found by the formula:

$$a_{ij}^{norm} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}. \tag{8}$$

2. Obtaining the eigenvector $V_m=\{v_{mi}\}$, $i=1, \dots, n$ of the matrix A_m^{norm} for the *m*-th parameter (property) by averaging over the rows:

$$v_{mi} = \frac{\sum_{j=1}^{n} a_{ij}^{norm}}{n}. \tag{9}$$

Then for all parameters, we obtain a matrix of eigenvalues of vectors or a matrix of importance of objects for all parameters:

$$V_n = \left|v_{ij}\right| = \begin{vmatrix} v_{11} & v_{12} & \dots & v_{1n} \\ v_{21} & v_{22} & \dots & v_{2n} \\ \dots & \dots & \dots & \dots \\ v_{m1} & v_{m2} & \dots & v_{mn} \end{vmatrix}, \tag{10}$$

where v_{ij}, $(i=1, \dots, m; j=1, \dots, n)$.

The resulting vector of importance takes into account the importance of tasks, the importance of criteria and the importance of objects for each of the criteria and is calculated by the formula:

$$W^P = W^{PR} \cdot V_n = \left[w_i^p, w_2^p, \dots, w_n^p\right]. \tag{11}$$

The algorithm for determining the importance (priority) of objects is shown in Fig. 2, 3.

Thus, the developed method allows you to make decisions in the process of modeling in those situations when it is necessary to carry out a multi-criteria selection of currently effective solutions and control strategies, determine the priorities of model elements, coordinate the actions of system objects, etc.

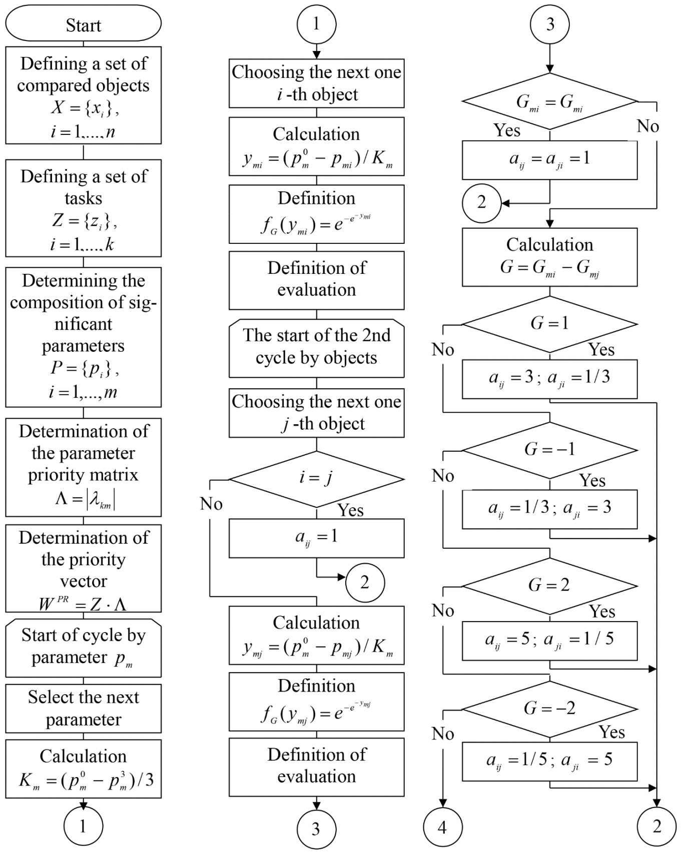


Fig. 2. Algorithm for determining the importance (priority) of objects

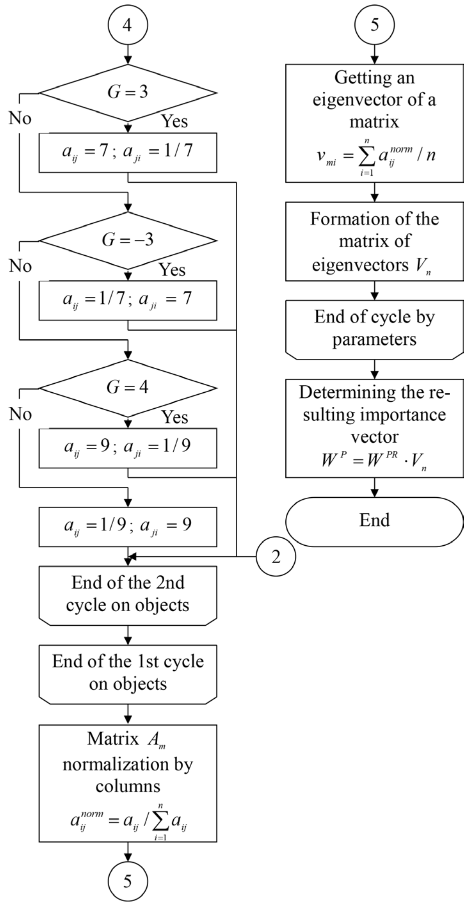


Fig. 3. Algorithm for determining the importance (priority) of objects (continuation)

5. 3. Experimental verification of the method in the task of risk assessment of gas pipeline sections

This method is used in an automated system of electrochemical protection of main pipelines [18]. The main gas pipeline is considered, divided into sections according to the protection arms, which are provided by cathodic protection stations installed on each of them. Fig. 4 shows a situational plan of one of the sites, with conditional images: places of installation of a cathodic protection station, control and measuring points, crossings over roads and rivers, intersections with power lines, etc. There is a graph of the distribution of the protective potential on the site. In addition, information on soil type is provided, with recording sections of pipelines laid in chernozems, swampy and irrigated soils, a map of corrosiveness is given, indicating the measured soil resistivity. Areas are recorded where there are:

– dangerous corrosive effect of alternating current;

– positive-bias stray current;

– the risk of microbiological corrosion;

– industrial and domestic drains, landfills of garbage and slag laid at a distance of up to 1 km;

– the temperature of the transported product is above 30 °C and more.

Thus, all of the above is the initial data to start work on the method of risk assessment of pipeline sections.

Fig. 5 shows the stage of forming the structure of evaluation factors. This model is designed to determine an integrated estimate of the risk (danger) of PLS facilities, in particular gas pipeline sections that require restoration, based on a set of object factors (properties).

The list of factors includes the following groups: constructive and technological; operational; corrosion effects; external environment; human; environmental impact.

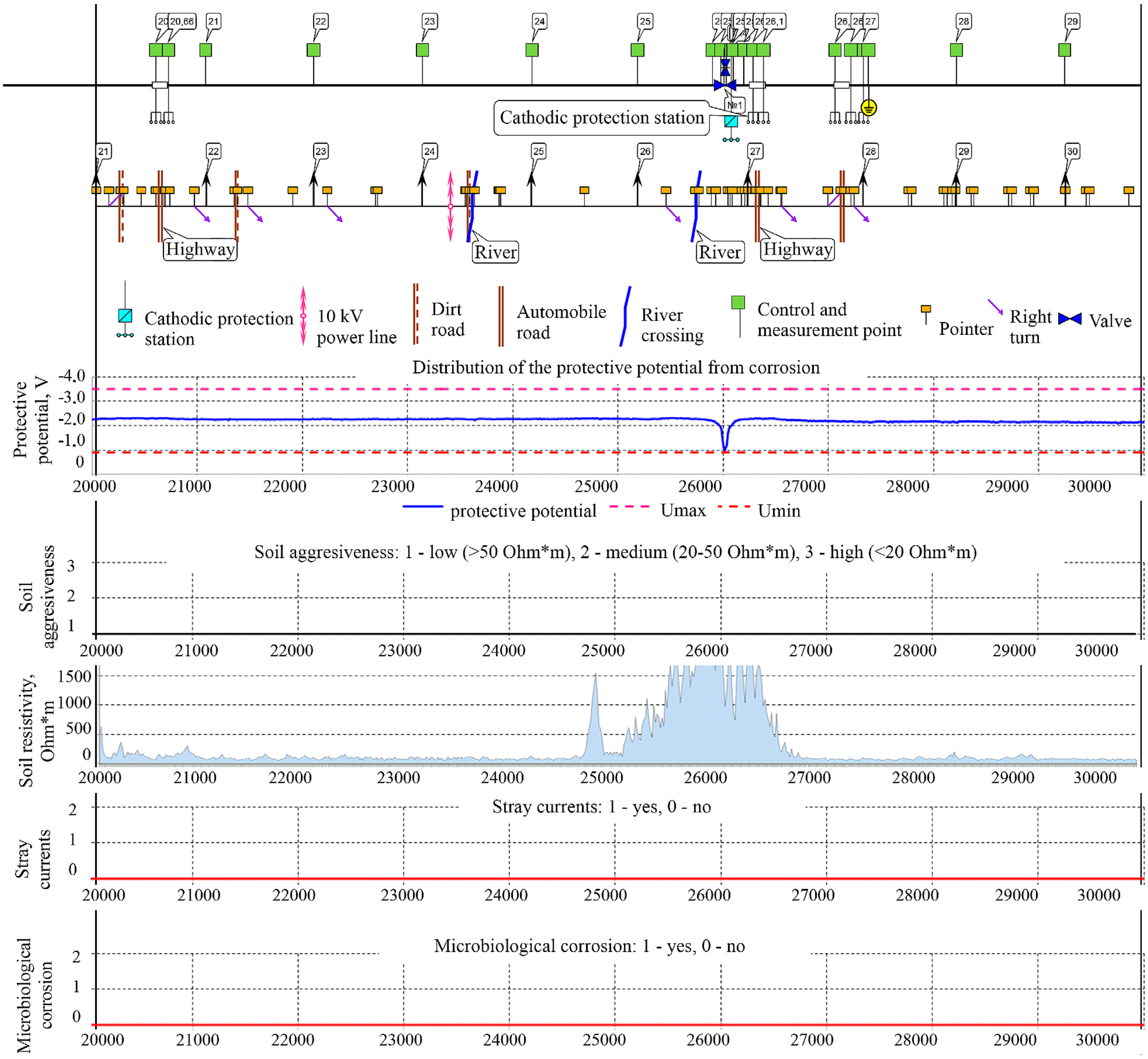
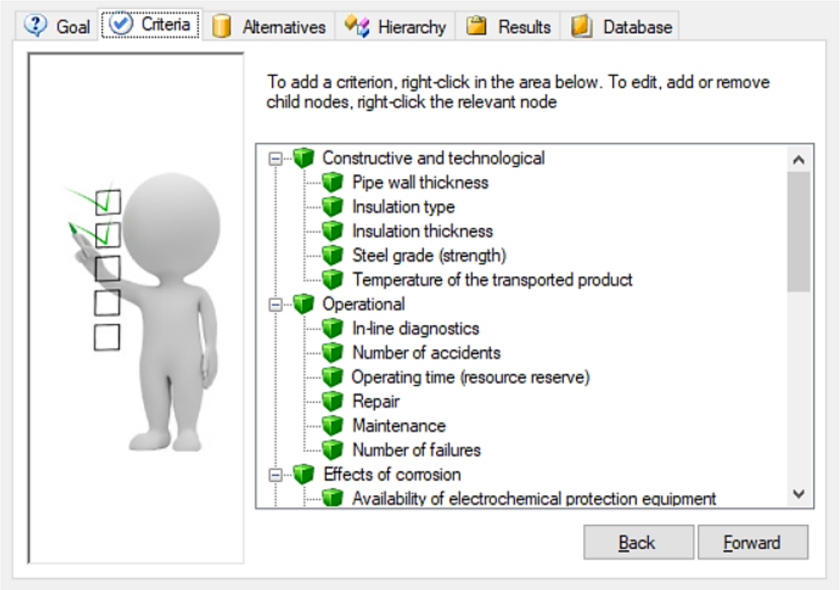


Fig. 4. Example of information on the pipeline section in risk assessment



To add a criterion, right-click in the area below. To edit, add or remove child nodes, right-click the relevant node

- Constructive and technological
  - Pipe wall thickness
  - Insulation type
  - Insulation thickness
  - Steel grade (strength)
  - Temperature of the transported product
- Operational
  - In-line diagnostics
  - Number of accidents
  - Operating time (resource reserve)
  - Repair
  - Maintenance
  - Number of failures
- Effects of corrosion
  - Availability of electrochemical protection equipment

Fig. 5. Formation of the structure of assessment criteria

A total of 30 factors are considered (Table 3), where the importance was obtained by applying the method proposed in this study by experts of the operating organization.

Fig. 6 shows the stage of forming alternatives – gas pipeline sections for risk assessment.

Table 3

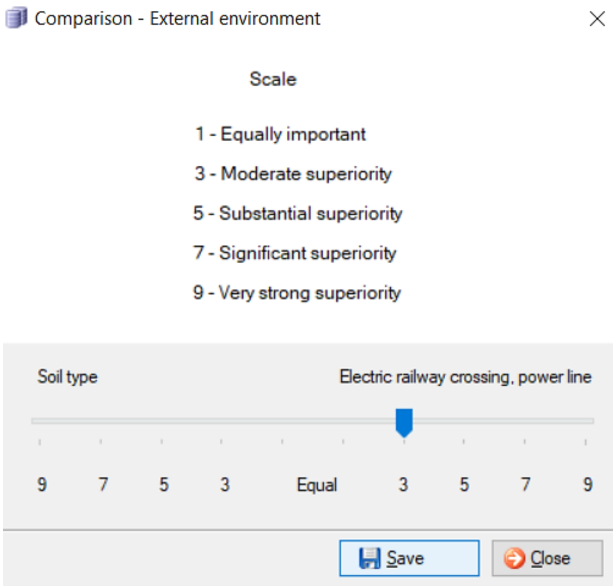
Risk assessment factors of pipeline sections and their importance

No.	Factor (property) of the pipeline section	Importance
1	Proximity of settlements	0.0408
2	Proximity of industrial facilities	0.0295
3	Compliance with regulatory requirements	0.0406
4	Number of failures	0.0421
5	Availability of electrochemical protection means	0.1360
6	Underwater crossing	0.0110
7	Insulation status	0.0771
8	Degree of corrosion	0.0989
9	Soil type	0.0097
10	Specific electric resistance of soil	0.0161
11	Type of electrochemical protection means	0.0330
12	Operating time (resource reserve)	0.0264
13	Pipe wall thickness	0.0138
14	Steel grade (strength)	0.0138
15	Personnel qualification	0.0406
16	Consequences of the explosion	0.0294
17	In-line diagnostics	0.0121
18	Number of accidents	0.0527
19	Presence of stray currents	0.0253
20	Railway, highway, telecommunications crossing	0.0178
21	Consequences of the fire	0.0294
22	Temperature of the transported product	0.0138
23	Insulation type	0.0548
24	Insulation thickness	0.0344
25	Air (aboveground) crossing	0.0081
26	Amount of water-soluble salts	0.0089
27	Presence of bacteria (microbiological corrosion)	0.0105
28	Electric railway crossing, power line	0.0314
29	Repair	0.0258
30	Maintenance	0.0159

An example of comparing criteria with each other on a scale of relative importance is shown in Fig. 7.

Assessment is carried out by an expert or a group of experts (in this case, a generalized opinion is formed).

To form a paired comparison matrix for the selected parameter, the values of the expert assessment of the parameter are analyzed on the basis of a scale of relative importance.



Comparison - External environment

Scale

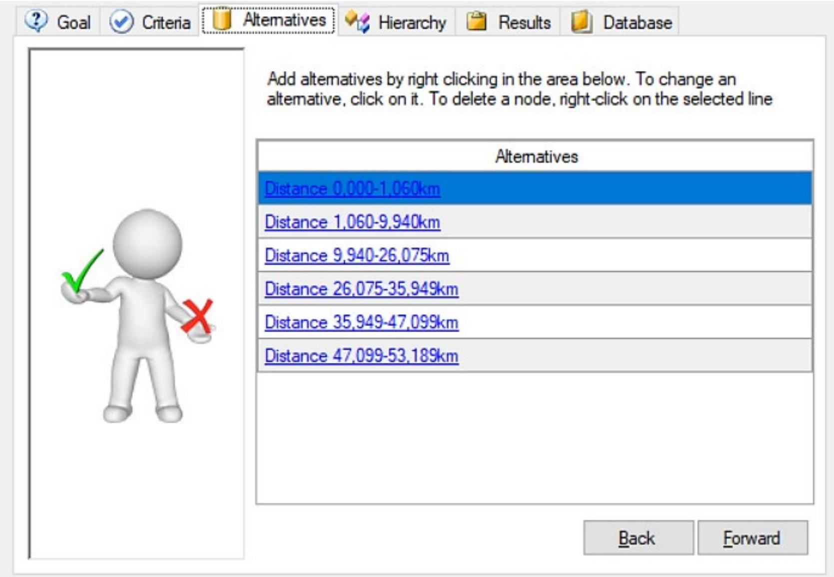
1 - Equally important
3 - Moderate superiority
5 - Substantial superiority
7 - Significant superiority
9 - Very strong superiority

Fig. 7. Example of comparing criteria with each other on a scale of relative importance

After all expert judgments are formed, the calculation of the priority vector is initiated.

The results of the comparison are recorded in the hierarchy of the decision-making task for the PLS risk assessment (Fig. 8).

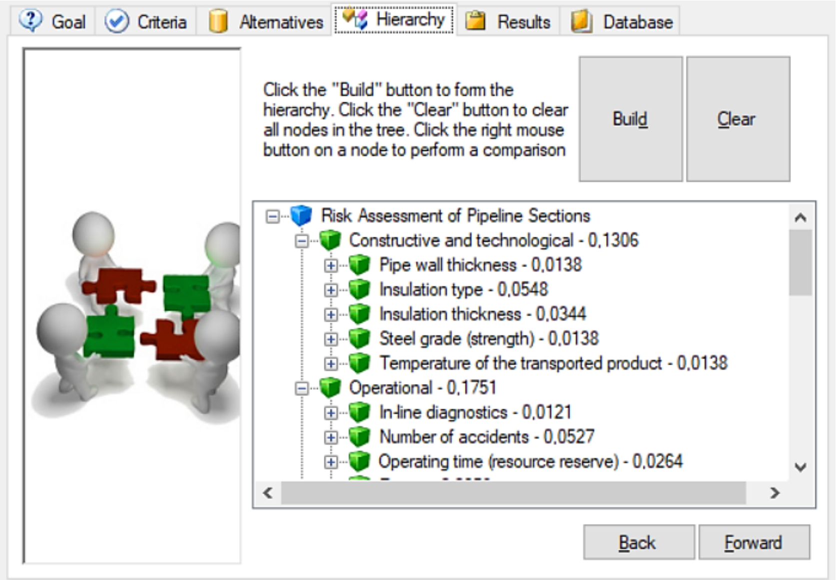
An example of calculating the importance vector of factors affecting the assessment of the required protective potential «pipe-to-ground» for a gas pipeline section is presented in Table 4.



Add alternatives by right clicking in the area below. To change an alternative, click on it. To delete a node, right-click on the selected line

Alternatives
Distance 0,000-1,060km
Distance 1,060-9,940km
Distance 9,940-26,075km
Distance 26,075-35,949km
Distance 35,949-47,099km
Distance 47,099-53,189km

Fig. 6. Formation of alternatives – gas pipeline sections



Click the "Build" button to form the hierarchy. Click the "Clear" button to clear all nodes in the tree. Click the right mouse button on a node to perform a comparison

- Risk Assessment of Pipeline Sections
  - Constructive and technological - 0,1306
    - Pipe wall thickness - 0,0138
    - Insulation type - 0,0548
    - Insulation thickness - 0,0344
    - Steel grade (strength) - 0,0138
    - Temperature of the transported product - 0,0138
  - Operational - 0,1751
    - In-line diagnostics - 0,0121
    - Number of accidents - 0,0527
    - Operating time (resource reserve) - 0,0264

Fig. 8. Constructed hierarchy where the assessment is carried out on a quantitative or qualitative scale

Table 4

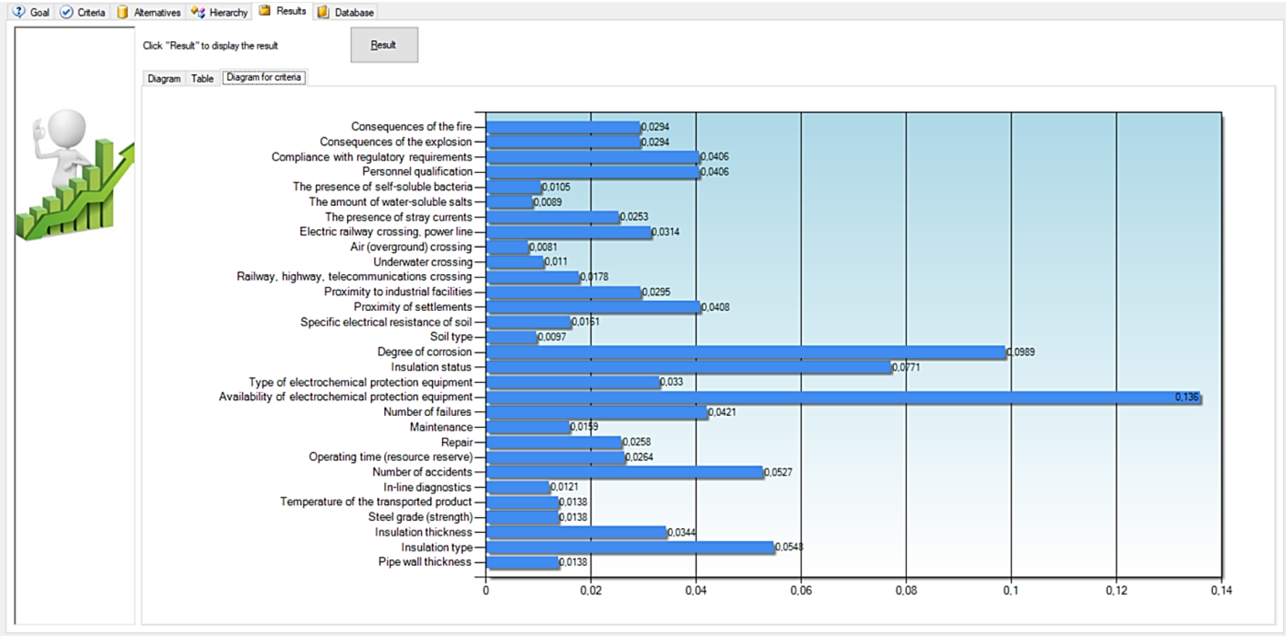
Generalized importance vector of factors affecting the assessment of the required protective potential «pipe-to-ground» for a gas pipeline section

Factor name	Importance vector of factors of the first expert	Importance vector of factors of the second expert	Generalized importance vector of factors
GT	0.42	0.418	0.414
IT	0.20	0.198	0.199
SCP	0.10	0.109	0.105
SR	0.11	0.108	0.107
WSSC	0.06	0.068	0.066
MBCP	0.05	0.054	0.053
GWL	0.04	0.035	0.036
SST	0.02	0.018	0.018

Note: GT – gas temperature; IT – insulation type; SCP – presence of stray currents; SR – soil resistivity; WSSC – content of water-soluble salts; MBCP – possibility of microbiological corrosion; GWL – groundwater level; SST – tensile strength of steel

Fig. 9 presents a list of significant criteria and their importance for the task of risk assessment of gas pipeline sections, obtained from the results of expert assessment and displayed in the form of a diagram using the created model. From these results, one can judge the importance (significance) or priority of PLS objects, if modernization, resource allocation, etc. are necessary.

The method of forming the degree of risk is similar to importance assessment, but the experts assign points to the compared alternatives in terms of the magnitude of danger. The results of the risk assessment of gas pipeline sections for the considered example are shown in Fig. 10.



Click "Result" to display the result

Fig. 9. Importance of criteria for the risk assessment of a gas pipeline section

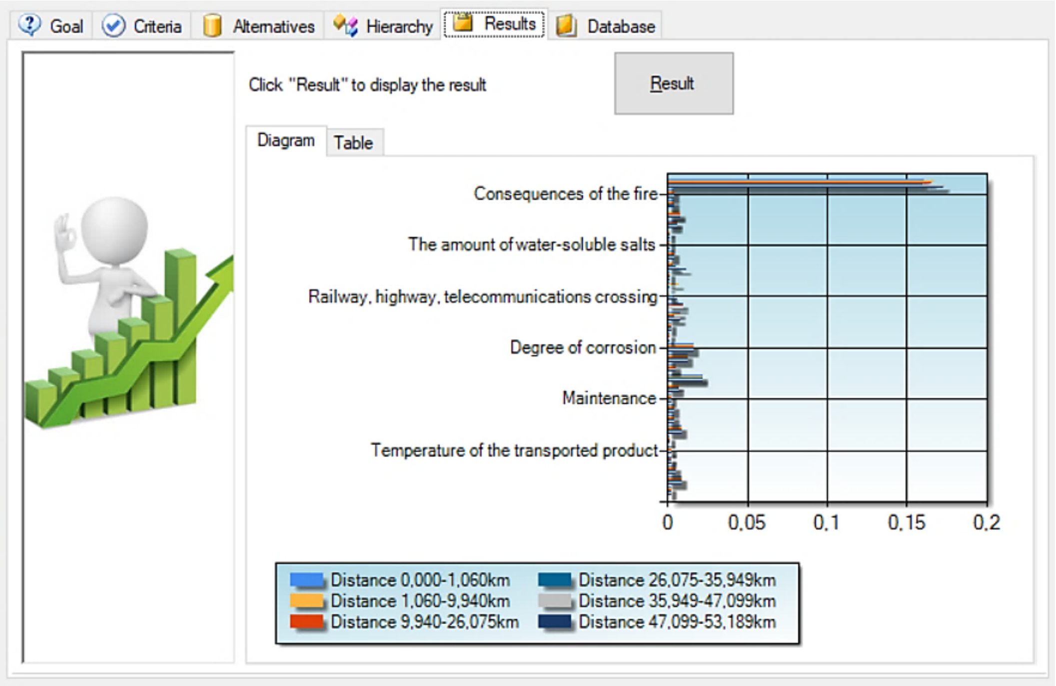


Fig. 10. Result of risk assessment of specific gas pipeline sections

The obtained estimates of alternatives (gas pipeline sections) are displayed in the form of a bar chart for each of the criteria and in total.

To assess the risks, we used the improved AHP-based method described in this paper, which is based on a comparative assessment of experts' judgments on a priority scale about the compared objects, taking into account their risk or danger.

6. Discussion of the results of developing a method for assessing the importance and risks of main pipeline facilities

A method to overcome the difficulties of automating the process of evaluating pipeline system objects by criteria is proposed, which provides a transition from evaluating objects by physical parameters to dimensionless assessment. This makes it possible to exclude experts from the process of filling in the paired comparison matrix based on the formation of a system of rules and using the Harrington function (Fig. 1). Having a priority vector of criteria importance and guided by a system of rules for comparing objects, it is enough only to specify the actual values of criteria for each alternative. This approach allows you to form a pool of decision-making and importance assessment tasks, which can be used ready-made not only by specialists. This greatly simplifies the complexity of solving the problems of evaluating PLS objects while maintaining sufficient reliability of the results and is an advantage of this study in contrast to the methods presented in [10, 11]. In addition, this eliminates the duplication of assessment stages and the degree of subjectivity in the problems of forming importance vectors of evaluation criteria.

A hierarchical system of criteria for risk assessment of PLS facilities is proposed by considering six important aspects that determine the safety status of oil and gas pipelines: constructive and technological; operational; corrosion effects; external environment; human; environmental impact. The value of each criterion is determined by studying the relevant pipeline technical data and in combination with expert experience, as shown in Fig. 4, 5. Risk assessment based on such a balanced system of criteria avoids the low reliability of the evaluation results, which can be expected by researchers using only one direction or a small number of criteria. Thus, it should be noted that most researchers, when assessing the risk of PLS, consider the corrosion factor only as a fact of its external or internal manifestation at a specific site [3, 7]. Unlike these models, the proposed approach comprehensively takes into account the factors related to corrosion hazard, as well as the functioning and efficiency of the system and means of electrochemical protection. This gives significant advantages in solving the problem of evaluating PLS facilities, provides a complete understanding of the safety status of oil and gas pipelines and the reliability of results.

As a result of obtaining a generalized expert opinion, the importance vector of the criteria for risk assessment of PLS facilities was obtained (Fig. 9). After normalization, the following criteria have the highest importance values: the operating condition of electrochemical protection equipment, the degree of corrosion, the condition of the insulation coating and the number of accidents at the site. For the considered task of risk assessment for the main oil pipeline, the operating condition of electrochemical protection means is based on the analysis of the condition of such equipment as:

– cathodic protection stations;

– tread protection devices at intersections with roads and railways;

– pipeline protection devices for removing alternating current induced as a result of electromagnetic effects of high-voltage power lines.

In addition to the fact that the proposed approach eliminates the human factor when filling in paired comparison matrices, it can sort the importance of various risk factors. This enables specialists to better understand potential risks and provide appropriate management and control proposals.

The study shows how this technique, as well as the developed importance assessment and decision-making software, are used in an automated system of electrochemical protection of main pipelines.

An empirical study was conducted on the main line of the oil trunk pipeline with a length of about 53 km. The study was conducted to determine the risks and the order of restoration of individual pipeline sections. Six sites were considered in accordance with the protection arms of the cathodic protection stations installed on them. The analyzed oil trunk pipeline runs through flat terrain, has intersections with roads and railways, high-voltage power lines, and also crosses water barriers. The results of the survey included the condition and locations of defects in the insulation coating, the state of electrochemical protection equipment, data on the corrosion situation on the highway, etc. The results of the assessment (Fig. 10) show that oil pipeline sections 1, 3 and 4 have a low risk. Pipe section 2 has a medium risk, and the highest risk value is in sections 5 and 6. This is due to the greater corrosion hazard in these areas. In turn, this requires taking appropriate precautions and establishing special control procedures to reduce the risk of accidents in these areas. Due to the coordination of risk assessment data and results of field surveys, it was possible to form a plan for scheduled and recovery work. It is also recommended to perform drilling operations for an additional examination of the condition of the insulating coating and metal of the pipe, as well as additional measurements of the protective potential by the method of an external reference electrode.

As shown in Table 3, this approach can be used not only for evaluating PLS sections, but for any particular tasks. For example, obtaining an importance vector of factors influencing the assessment of the required protective potential «pipe-ground» for a gas pipeline section. In the future, this can be used in scenarios of automated control of cathode stations of electrochemical protection.

The software allows you to accumulate a knowledge base about the importance of criteria in solving various tasks (risk assessment, threat identification, accident analysis, etc.) and serves as an effective tool for services operating pipelines.

At the same time, it should be noted that the proposed method not only solves the problem of quantitative risk assessment, but also can identify shortcomings of individual indicators, which helps specialists to carry out targeted improvements. The results obtained given in the paper allow us to assert the effectiveness of using this method and the corresponding software as part of an automated system of electrochemical protection of main pipelines. However, this does not limit the possibility of using the method and software in other production and technological systems.

As a limitation of the approach, the presence of a certain subjectivity associated with expert assessments of the analyzed parameters on the desirability scale should be noted. The same applies to the selection of the analyzed parameters themselves, which depends on the purpose of assessment. Thus, it is necessary to further explore how to combine existing information about parameters to form a more complete assessment method. It should be noted that at this stage, various specialists of MPL linear production management services were involved as experts in order to form a list of factors for the task of risk assessment of MPL facilities. These actions were also performed using the proposed method and software. This paper already shows which of the factors of each of the groups were taken as decisive for the final task of assessing the importance and risks of PLS facilities.

At the same time, it should be noted that the decision-maker may not be confident in his judgment. To investigate this point, it would be necessary to conduct a sensitivity analysis to see if the outcome of the choice changed when the decision-maker's judgment was somewhat altered. The absence of such an analysis in the work can be considered a disadvantage that can be eliminated in further research.

The development of this study is planned to switch to the cloud architecture of the illustrated decision support system. It is possible to implement the template mechanism, which will allow users to get a ready-made prototype of the model from the existing pool and adapt it according to their own understanding of the essence of the problem and the requirements for solving it. The models can easily be placed in the cloud, synchronized with user devices, provide an opportunity to invite participants to the evaluation project, and view the results on mobile devices.

Thus, the developed method allows you to make decisions in situations where it is necessary to carry out a multi-criteria selection of currently effective solutions and management strategies. It also allows you to assess risks, prioritize elements and coordinate actions for modernization or development.

7. Conclusions

1. A feature of this method is the use of well-known methods of ranking objects, such as the analytic hierarchy process and convolution method based on the well-known Harrington membership function. Thus, in order to reduce the original multi-criteria decision-making problem with multi-dimensional criteria to a multi-criteria problem with criteria measured on a single dimensionless scale, the Harrington desirability scale was used. To build it, it is enough for experts to indicate only two boundaries of the initial indicators. These values correspond to the rectilinear section of the membership function and provide the same sensitivity of expert assessments. The steepness of the dependence of the desirability function on the value of the object parameter in the «bad» area is noticeably greater than the steepness of the curve in the «good» area. This is a reflection of the mathematical properties of the Harrington function, which are important in terms of its practical use for our purposes.

2. In order to exclude experts from the process of filling in paired comparison matrices, the process of developing expert judgments on the assessment of object importance was formalized. For this purpose, rules (axioms) were developed to automate the process of obtaining expert judgments, as well as the importance of criteria and the importance of pipeline facilities (sections) themselves. This approach makes it possible in the future to proceed to the formation of an expert knowledge base for various object evaluation tasks, which can be used by various specialists in a ready-made form.

3. The proposed method was tested in solving the problems of determining the risks and priority of restoration of individual pipeline sections affected by corrosion as part of the information and analytical system for monitoring and controlling the electrochemical protection of trunk

pipelines of the Republic of Kazakhstan. The results of experimental studies have shown that this method makes it possible to effectively solve the problem of planning restoration repairs on pipeline sections, reducing the risk of accidents by up to 30 %.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, copyright or other, which could affect the research and its results presented in this paper.

Financing

The paper presents the results of a study conducted within the framework of the grant project of the Ministry of Education and Science of the Republic of Kazakhstan AP09261098 on the topic «Development of an information and analytical system for monitoring and controlling electrochemical protection against corrosion of trunk pipelines».

Data availability

The manuscript has no associated data.

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