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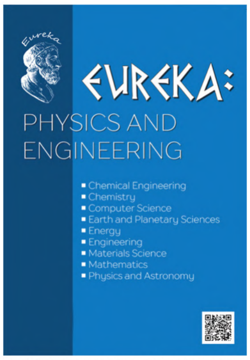

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CONTENT

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DEVELOPMENT OF A POTENTIOMETRIC SENSOR SENSITIVE TO POLYSORBATE 20

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Abstract

Polyoxyethylated sorbitans (polysorbates) are widely used in the chemical, pharmaceutical, and cosmetic industries, but only quantitative determination is used mainly for chromatographic methods. In this paper, the results of the development and testing of a potentiometric sensor sensitive to nonionic surfactant polyoxyethylene sorbitan monolaurate (polysorbate-20) are presented. An anion of the heterogeneous acid of the Keggin structure (12-molybdophosphate heteropolyacid) was used as a counterion to obtain the electrode-active substance for the potentiometric sensor membrane. Polysorbate-20 does not form cations when dissociating in water and cannot directly interact with heteropolyanion; therefore, a cationic complex of polysorbate-20 with barium ions was previously prepared (similar to the interaction of metals with crown ethers). The resulting ion associate meets the basic requirement for the electrode-active substance of plasticized film polyvinyl chloride membranes of potentiometric sensors (poor water solubility and good solubility in organic solvents). Phthalic acid derivatives (dibutyl phthalate and dioctyl phthalate) were used as solvent-plasticizers for a polyvinyl chloride membrane. To determine the optimum conditions for the functioning of a potentiometric sensor sensitive to polysorbate-20, the influence of various factors on the electrode characteristics was studied. Quantitative content of the ionic associate in the polyvinyl chloride membrane, the nature of the membrane solvent-plasticizer, pH of a series of standard polysorbate-20 solutions) on the electrode characteristics of the plasticized membrane of the potentiometric sensor (sensitivity or slope of the electrode function, lower limit of linearity and minimum detectable concentration of polysorbate-20, which can be determined with the help of the developed potentiometric sensor) was studied. The optimal conditions for using the developed potentiometric sensor were found. The developed sensor allows for a short period of time (5–10 min) determining the quantitative content of polysorbate-20 in industrial products at the level 10–5–10 6 mol/l. The potentiometric sensor sensitive to polysorbate-20 can be used for the development of a potentiometric method for determining the clinical reception of polysorbate-20 in various types of industrial products.

Keywords: 12-molybdophosphate heteropolyacid, polyoxyethylene sorbitans, polysorbate, potentiometric sensor, direct potentiometry, tween.

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1. Introduction

Polysorbates (trade name "tween") are ethoxylated sorbitans exhibiting the properties of non-ionic surfactants. These compounds are widely used in industry as fiber softeners, defoamers, antistatic agents, emulsifiers and solubilizes [1].

Polyoxyethylene sorbitan monolaurate (Polysorbate-20) is a non-ionic surfactant with a degree of ethoxylation at 20 (**Fig. 1**). It was chosen as the object of a study.

Polysorbate-20 is used in the cosmetic industry [1–4]: to improve the dissolution of essential oils; in foam-washing compositions, which are moisturizing well, don't irritate and don't overdry the skin; in decorative cosmetics.

Currently, IR spectroscopy is used to identify ethoxylated sorbitans [5], and high-performance liquid chromatography [6–10] is used to quantify the content. According to previous studies [11–20], direct potentiometry using sensors which are sensitive to organic cations and substances is a simple, rapid and sensitive method of determination. The purpose of this study was to develop a potentiometric sensor which would allow to quickly and efficiently determine polysorbate-20 in various environmental objects and industrial products.

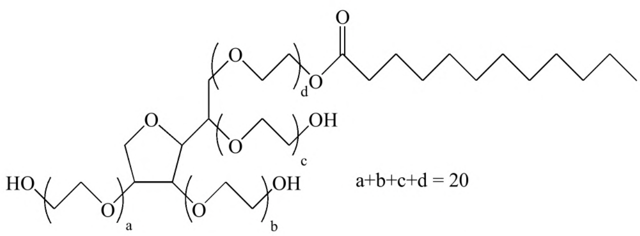

Fig. 1. Polysorbate 20 structural formula

Inasmuch as the ethoxylated sorbitans are non-ionic surfactants and don't form ions upon dissolution, a cationic complex of polysorbate-20 with barium ions was obtained in advance to obtain an associate with a 12-molybdophosphate heteropolyacid.

2. Methods, materials, and devices, used for making and testing of the potentiometric sensor for polysorbate 20 detection

2. 1. Materials used for developing and testing of the potentiometric sensor for polysorbate 20 detection

The following reagents are used in the work:

– 12-molybdophosphate acid, $H_3PMo_{12}O_{40}\times 26H_2O$ (analytically pure);

– Polysorbate-20, C58H114O26 (pure grade);

– Sodium hydroxide (analytically pure);

– Chloride acid (conc.) (analytically pure);

– Barium nitrate (analytically pure).

The following reagents were used to manufacture membranes potentiometric sensors:

– PVC (polyvinyl chloride), brand C-70 (pure grade) is a membrane matrix;

– CH (cyclohexanone), (analytically pure) is a matrix solvent.

The phthalic acid esters are used as membrane solvent-plasticizers:

– dibutyl phthalate (DBF), pure grade;

– dioctyl phthalate (DOF), pure grade.

Ionic associate of the cationic complex of polysorbate with barium ions and 12-molybdophosphate acid was used as an electrode active substance.

2. 2. Devices used for making and testing of the potentiometric sensor for polysorbate 20 detection

An electrochemical cell (**Fig. 2**) was used for direct potentiometric studies:

Ag	AgCl, KClsat.	Investigated solution	Membrane	$5.0\cdot10^{-5}$ solution PS-Ba^{2+}	AgCl, KClsat.	Ag

Fig. 2. The electrochemical circle of special cell for direct potentiometry

The galvanic cell consisted of a film potentiometric sensor (with an internal solution $5.0\cdot10^{-5}$ M solution of the test substance and an internal electrode – Ag/AgCl wire in $KCl_{sat.}$) and silver chloride reference electrode EBL-1M31 with KCl saturated solution. Measurement of EMF is carried out with the ionomer I-130. To determine the pH has used the electrode with brand ESK-10601/4.

2. 3. Method for the synthesis of a plasticized membrane potentiometric sensor sensitive to polysorbate-20

Plasticized polyvinyl chloride membranes were synthesized according to the following procedure: 0.45 g of polyvinyl chloride was dissolved in 4.5 ml of cyclohexanone with weak heating (does not exceed 60 °C) with constant stirring up to complete dissolution. Separately, we prepared a solution of a sample of 0.01 g or 0.10 g of the ionic associate in 1.1 ml of a plasticizer solvent. The phthalic acid esters were chosen as a plasticizer solvent via dibutyl phthalate (DBF) or dioctyl phthalate (DOF). The solutions were mixed and transferred to Petri dishes with a diameter of 50 mm in the form of a transparent homogeneous liquid mixture. A transparent elastic film of a plasticized PVC membrane was obtained from the mixture after complete evaporation of cyclohexanone in 2–3 days.

2. 4. Determination of optimal conditions for the functioning of the membrane of a potentiometric sensor sensitive to polysorbate-20

The membranes were soaked in a solution of polyoxyethylene sorbitan monolaurate with a concentration of $5.0\cdot10^{-5}$ mol/l before starting measurements for the correct operation of a potentiometric sensor. The electrode function of a potentiometric sensor depends on the properties of the ionic associate and on the nature of the plasticizer solvent for the membrane. The characteristics of potentiometric sensors sensitive to the cationic polysorbate - Ba^{2+} particle were studied on various model solutions. A series of standard solutions PS-20 with concentrations from $1.0\cdot10^{-6}$ to $5.0\cdot10^{-3}$ mol/l was used to build the calibration graphs inasmuch the critical concentration of micelle-forming of polysorbate-20 is ~$1.5\cdot10^{-3}$ mol/l. This fact means that micelles and molecules appear in the solution which can influence on the determination results. Barium nitrate with volume 1.0 ml and concentration at 0.1 mol/l was added to 25.0 ml of each solution in the series to obtain a cationic complex.

The electrode characteristics of the developed sensors (minimum detectable concentration, linearity interval, and sensitivity S) were investigated depending on the various factors to determine the optimal conditions.

3. The results of the development of a potentiometric sensor sensitive to polysorbate20: determination of optimal conditions for the functioning of the membrane

3. 1. Study of the influence of various factors on the slope of the electrode membrane function of a potentiometric sensor sensitive to polysorbate 20

Fig. 3, 4 shows the study results of the effect of pH of the test solution, the nature of the membrane solvent and the quantitative content of the ionic associate in the membrane on the amount of slope (steepness) of the electrode function of the potentiometric sensor sensitive to polysorbate-20.

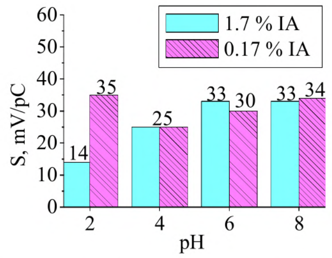

Fig. 3. Dependence of the slope of the electrode function from various factors (plasticizer solvent – dioctyl phthalate)

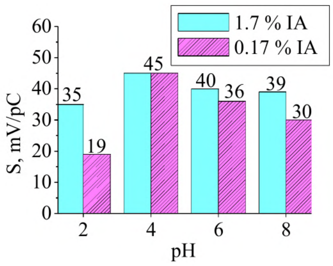

Fig. 4. Dependence of the slope of the electrode function from various factors (plasticizer solvent – dibutyl phthalate)

In the study of the influence of pH of solutions of the standard polysorbate-20 series, it can be seen that the numerical values of the inclination of the electrode function close to the theoretical one are observed at pH=6–8. The nature of the plasticizer solvent and the quantitative content of the ionic associate in the membrane do not have a significant effect on the inclination value of the electrode function of the developed potentiometric sensor sensitive to polysorbate-20

3. 2. The study of the dependence of the minimum determined concentration of polysorbate 20 on various factors

Fig. 5, 6 show the results of a study of the effect of the nature of the solvent, the content of the ionic associate in the membrane and the pH of the test solution on the minimum detectable concentration for the developed potentiometric sensors for polyoxyethylene sorbitan monolaurate.

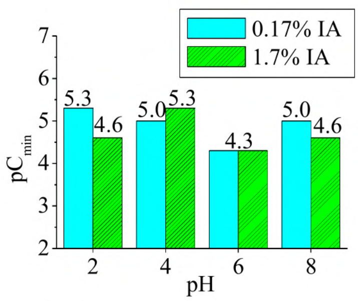

Fig. 5. The influence of various factors on the minimum detectable concentration of PS-20 (plasticizer solvent – dioctyl phthalate)

When investigating the effect of the nature of the solvent-plasticizer on the value of the minimum determined concentration, it was found that the lowest concentrations (the highest values of pC) were detected using dibutyl phthalate as a solvent. The acidity of the investigated solution and the quantitative content of the ionic associate in the membrane do not significantly affect this parameter.

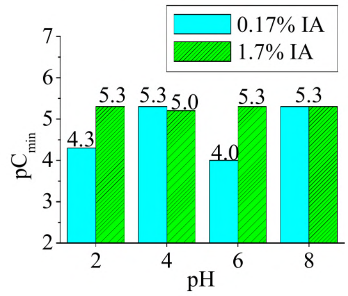

Fig. 6. The influence of various factors on the minimum detectable concentration of PS-20 (solvent – dibutyl phthalate)

3. 3. Investigation of the influence of various factors on the lower limit of the determination of potentiometric sensors sensitive to polysorbate-20

Fig. 7, 8 show the results of a study of the effect of the pH of the test solution, the nature of the solvent and the content of the ionic associate in the membrane on the lower limit of linearity for the developed potentiometric sensors for polyoxyethylene sorbitan monolaurate.

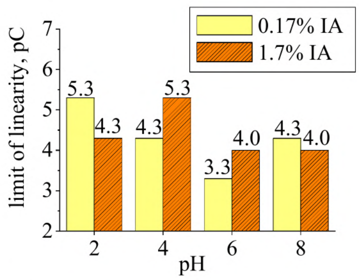

Fig. 7. The influence of various factors on the lower limit of the linearity of the E – pC dependence (solvent – dioctyl phthalate)

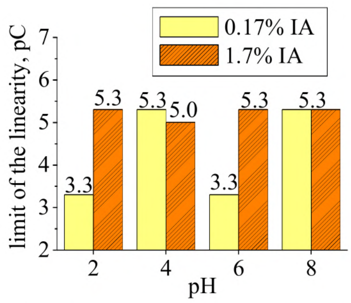

Fig. 8. The influence of various factors on the lower limit of the linearity of the E – pC dependence (solvent – dibutyl phthalate)

The study of the influence of various factors on the lower limit of the linearity of the electrode function showed that the maximum values of pC are observed with the use of a diluent-plasticizer of dibutyl phthalate, the quantitative content of the ionic associate in the membrane and the pH of the solution investigated do not significantly affect this parameter.

4. Discussion of development results and testing of a potentiometric sensor sensitive to polysorbate-20

It was found during the study of the influence of various factors on the steepness of the electrode function of the membrane of the obtained sensor that the slope value is 27–33 mV/pC for both solvents at a pH of 6 (for DOF) and 8 which corresponds to the theoretical Nernst's value for a double charged cation.

It can be seen from the obtained experimental data, that the best parameters (maximum range of operating concentrations of potentiometric sensors, the lowest detectable concentration (~5×10^{-6} mol/l) and the linearity of the calibration graph up to the concentration of 5.0×10^{-6} M) are observed for membranes with an inclination of the electrode function characteristic of a doubly charged cation under pH=6 and 8 and using of dibutyl phthalate as a membrane solvent and the content of the ionic associate is 0.17 % (0.01 g).

Accordingly, the optimal operating conditions of the potentiometric sensor for polysorbate-20 (linearity interval of the dependence $E=f(PC)$ from $5.0\cdot10^{-6}$ to $5.0\cdot10^{-3}$ mol/l with the slope of the electrode function $S\approx30$ mV/pC equal to the Nernst's value for doubly charged cations) are:

– m_{IA}=0.01 g (0.17 %);
– a solvent is dibutyl phthalate;
– pH=8.

In **Fig. 9** shows the dependence of the electrode potential of the developed potentiometric sensor for polysorbate-20 on the concentration of the test solution.

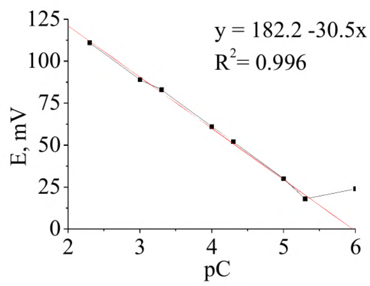

Fig. 9. The dependence of the electrode potential of the developed sensor on the logarithm of concentration (m_{IA}=0.01 g, solvent – DBF, pH=8)

It was experimentally established that the response time of the sensor is 30–50 s depending on the concentration of the test solution, the sensor's lifetime is ~50 days at stored dry and soaked for 10–15 minutes in a PS-Ba^{2+} solution with concentration $5.0\cdot10^{-5}$ mol/l.

5. Conclusions

The ion associate of the composition $(PS–Ba)_3(PMo_{12}O_{40})_2$ with Keggin structure has been synthesized. It was used as electrode active substances for the construction of polyvinyl chloride membranes of potentiometric sensors sensitive to polysorbate-20. The influence of various factors (the nature of the membrane solvent, the amount of associate in the membrane and the pH of a series of standard solutions) on the electrode characteristics (minimum detectable concentration, linearity interval, and sensitivity S) of the developed sensors was investigated. The optimum composition of the membrane of a potentiometric sensor and the conditions of its operation were selected (the content of the ion associate in the membrane is 0.17 %, a solvent is dibutyl phthalate and pH=8). The developed sensor can be used to determine the quantitative content of polysorbate 20 in various types of industrial products.

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THE PRINCIPLES OF DEVELOPING A MANAGEMENT DECISION SUPPORT SYSTEM FOR SCIENTIFIC EMPLOYEES

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Abstract

Employees engaged in mental work have become the most valuable assets of any organization in the 21st century. The satisfaction of those involved in mental work requires the provision of objectivity and transparency in their decision-making. This, in turn, entails the development of scientifically motivated decision making mechanisms and scientific-methodological approaches to evaluate their performance based on innovative technologies.

The main goal of this article is in development of the scientific and methodological framework for the establishment of a decision support system to manage the employees engaged in mental work and operating in uncertainty. In this regard, initially, the question of evaluating the activities of scientific workers is examined, its characteristic features are determined, and the fuzzy relation model is proposed as a multi-criterion issue formed in uncertainty. Taking into consideration the hierarchical structure of the criteria that allows evaluating the activities of scientific workers, a phased solution method based on an additive aggregation method is proposed. In accordance with the methodology, a functional scheme of the decision support system to manage the scientific personnel is developed. The working principle of each block and the interaction of the blocks are described. The rules for the employees' management decisions are shown by referring to the knowledge production model.

Based on the proposed methodological approach, the implementation phases of the decision support system for the management of the scientific workers of the Institute of Information Technology of ANAS are described. To evaluate the employees' performance, the tools to collect initial information, evaluate the system of criteria, define their importance coefficients and mathematical descriptions are provided. Some results of the system software are presented. The opportunities of the system based on the proposed methodology to support enterprise mangers to make scientifically justified decisions are provided.

Keywords: researcher, activity assessment, uncertainty, fuzzy relation model, additive aggregation, staff evaluation.

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1. Introduction

Objectives of human resource management (HRM) are the basis of personnel policy. The correct solution to these problems, making objective and transparency decisions on HRM allows the organization to achieve its global goals [1, 2]. In general, today the human resource management becomes the strategy of the company or firm. In this case, the funds invested in the development of human resources, transform into an investment, not expenditure [1]. The changes, occurred in the labor market, require major changes in the relationship with employees, in the policy of their recruitment, retention and motivation. In this regard, human resource management at the professional level has become a strong modern means used in HR. Fundamentally new attitude towards the personnel as valuable resource of the organization actualizes the importance of developing new conceptual approaches and technologies for HRM [2, 3]. Therefore, in recent years, computer technology is increasingly used for the HRM problem solutions.

The success of the twenty-first century, the age of information society and knowledge-based economy, refer to the increasing productivity of mental activity and the employees engaged in mental activity. The valuable asset of any commercial or non-profit organization is its mental work forces and their productivity. The productivity of the employees engaged in the mental activity is determined by the following six factors [4, 5]:

1. A clear answer to the question: What is "the essence of the production task?", i. e. how the "result" of the activity of the relevant organization (firm, enterprise, field)is defined?

2. Responsibility for the productivity depends of each employee himself/herself, that is, they are their own managers.

3. Uninterrupted innovative activity should be an integral part of the mental activity and must be included in the production task of any employee engaged in mental activity.

4. Employees engaged in mental activity always have to learn from and teach one another.

5. Productivity of employees engaged in mental activity is not measured quantitatively or quantitatively, i.e., its quality covers a broader scope and is defined by many parameters.

6. Finally, to increase the productivity of employees involved in mental activity, they need to be reviewed as "capital" rather than "expense" and should be treated accordingly. In this regard, employees should be encouraged to work in that organization and should regard it as the best option.

These factors represent the multi-dimensional, multi-criteria, and quantitative and qualitative character of the employees involved in mental activity. Depending on the fields of the organization, the productivity of its employees engaged in mental activity is characterized by different parameters. Increase in productivity primarily requires appropriate selection of these parameters and precise assessment of activity. Assessment of mental activity with the consideration of these aspects and requirements entails the objectiveness and transparency of the decisions made for the solution of the issues such as employees' satisfaction, promotion, rewarding, stimulation, deployment and redeployment, etc. All this requires the development of more innovative approaches to the evaluation of the activity of the employees involved in mental activity, and the development of decision mechanisms that meet the requirements set forth.

Thus, the **aim of this article** is in development of an intelligent decision support system for the management of the employees dealing with mental labor. To achieve this aim, the following issues are stated:

– to model a labor activity assessment of the employees dealing with mental labor;

– to develop a labor activity assessment technique;

– to implement an intelligent decision support system for the management of the employees referring to the results of labor activity assessment.

2. Modeling of researchers' activity assessment

Scientific employees, in particular, researchers who are professionally engaged in scientific and scientific-technical activities, are regarded as the resources of special importance in the industrialization of the country, the intellectual revival of the nation, and in the interstate competitiveness in economic, political and technological fields, and in enhancing the innovation capabilities of the state. Establishment and strengthening of the knowledge society and knowledge-based economy, ensuring its sustainable, dynamic and competitive development, and the realization of the prioritized role of science are determined by the scientific achievements [6].

Thus, the study of the problems related to the management of the employees engaged in scientific activity, the identification of the features characterizing their activities, and the objectiveness and transparency of the employees' management decisions require the development of the mechanisms for activity assessment. Objective and truthful assessment of the productivity of mental activity, which provides the professional progress of scientific employees and achieving their goals in accordance with prospective strategy, constitutes the basis for the personnel policy in this segment [5, 7, 8].

As it is mentioned, when evaluating the researchers' performance, the direct assessment subject is activity, and its quantitative assessment becomes problematic.

The activity of scientific employees differs according to scientific areas (fundamental, applied and experimental research, etc.) and types (humanities, nature, medicine, social and technical sciences). This difference is particularly represented in the analysis of the objective and subjective conditions of scientific and technical activity and complicates the assessment of the performance of scientific employees.

As it is mentioned, the most important feature characterizing the activity of scientific employee is the fact that their achievements are difficult and sometimes impossible to be measured with certain quantities. Thus, sometimes, the results of activity are not revealed at once, but after some time, and even much later [4].

Therefore, the parameters selected to evaluate the activity of employees should ensure democracy, transparency and objectivity of the assessment system, and provide the same and fair attitude to all employees enabling the managerial decisions based on the evaluation results [9, 10].

The diversity of the activity of employees is determined by the use of quantitative and qualitative criteria in the assessment, by their usual hierarchic character and their relevance. Analysis and evaluation of the activity based on such criteria requires certain time. The changes and external influences during this period do not allow for exact depiction of the problem. The issue is realized in uncertain circumstances and becomes the problem of decision-making in a fuzzy environment [11–17].

Thus, the evaluation of the activity of scientific employees requires referring to the fuzzy apparatus taking into account the hierarchical and fuzzy nature of the criteria, and the linguistic uncertainties regarding the formalization of the expert knowledge. Such an expression of the problem ensures the problem to be solved by being reduced to the problem of fuzzy multicriteria optimization and ranking. Here, the optimization is not a matter of mathematical optimization, but a selection of the alternative options [13, 14].

Fuzzy multicriteria optimization techniques are based on the aggregation of an affiliation function by referring to the fuzzy relation model. According to the fuzzy relation model, $X=\{x_1,x_2,\ldots,x_n\}=\{x_i, i=\overline{1,n}\}$ and $K=\{k_1,k_2,\ldots,k_m\}=\{k_j, j=\overline{1,m}\}$ s a set of the alternatives, out of which the best one should be selected, whereas is a set of criteria characteristic to the alternatives (K is a summarizing criterion), then the correspondence of these alternatives with the criteria can be presented by a two-dimensional matrix. The element of this matrix is determined by the affiliation function, which represents the extent of correspondence of the alternative x_i with the criterion k_j: $\phi_{k_j}(x_i): X\times K\rightarrow[0,1]$. Here, $\phi_{k_j}(x_i)$ represents the extent of correspondence of the alternative x_i with the criterion k_j [15].

3. The technique for the assessment of researchers' activity based on the fuzzy relation model

The **key stages** of the solution of the problem of activity assessment of scientific employees are as follows:

1) formation of the structural scheme of the evaluation system, namely, the alternatives: the list of employees, whose activity is evaluated, the evaluation criteria system, imposed restrictions and objectives;

2) selection of methods for the acquisition (selection of experts, expert evaluation, selection of quantitative and qualitative levels of criteria) and processing (mathematical representation of criteria, determination of relative importance coefficient of criterion) of initial information;

3) selection of a method that enables an integral evaluation of the results for the criteria out of certain evaluation set.

Stage 1 identifies the followings:

1) $X=\{x_i, i=\overline{1,n}\}$ is a set of alternatives, more precisely, the employees engaged in scientific-theoretical, scientific-practical, practical and educational activities in a research institution;

2) $K=\{K_j, j=\overline{1,m}\}$ is a set of criteria with different weight characteristic to the alternatives (K-summarizing criterion);

3) each criterion $K_j, j=\overline{1,m}$ is determined based on the different weighted sub-criteria that can be evaluated, i. e., $K_j=\{k_{jt}, t=\overline{1,T}\}$.

Stage 2. A single quality measurement scale (SQMS) approach can be attributed to an expert evaluation of the mathematical description of the sub-criteria characterizing the activity. This approach:

a. selects SQMS representing the transition of linguistic values (for example, 3-level – "good", "normal", "weak"), which corresponds to the intensity level (3, 5, 7, 9 levels are available) of the quality indicator of our natural language and is defined within the interval [0,1], to the fuzzy numeral;

b. approves sub-criteria as linguistic variables, and divides them into intensity levels in accordance with SQMS, and adopts appropriate linguistic values and fuzzy numbers per level.

To determine importance coefficients of the criteria, 10-score system uses the expert evaluation method or a pairwise comparison criterion [18].

This stage defines the following:

1) affiliation function of alternatives to the assessible alternatives $\left\{k_{jt}, t=\overline{1,T}, j=\overline{1,m}\right\}$:

$$\left\{\phi_{k_{j1}}\left(x_i\right), \phi_{k_{j2}}\left(x_i\right), \ldots, \phi_{k_{jT}}\left(x_i\right)\right\}=\left\{\phi_{k_{jt}}\left(x_i\right), t=\overline{1,T}, j=\overline{1,m}\right\}; \tag{1}$$

2) importance coefficient of the criteria, i. e.

$$\left\{w_1, w_2, \ldots, w_m\right\}=\left\{w_j, j=\overline{1,m}\right\} \tag{2}$$

and importance coefficient of the sub-criteria included in the same group:

$$\left\{w_{j1}, w_{j2}, \ldots, w_{jT}\right\}=\left\{w_{jt}, t=\overline{1,T}, j=\overline{1,m}\right\} \tag{3}$$

and the condition

$$\sum_{t=1}^{T} w_{jt}=1$$

is provided to the sub-criteria that characterizes the same criterion.

The **goal** is in obtaining a ranked list of employees based on the affiliation of the scientific employee to the summarizing criterion *K*, i. e., the determination of $\phi_K(x_i) \rightarrow [0,1]$. That is: *X: K→X**, where *X** is the adjusted list of employees.

Stage 3. The method proposed for the evaluation of activity of scientific employees requires an assessment of the alternatives, taking into account the hierarchical structure of the criteria and their diverse importance. In this regard, the additive aggregation method is referred and the problem is solved in the following sequence [19, 20]:

1. According to (1) and (3), the affiliation function of the alternative x_i to K_j is defined as:

$$\phi_{K_j}\left(x_i\right)=\sum_{t=1}^{T} w_{jt}\, \phi_{k_{jt}}\left(x_i\right). \tag{4}$$

2. According to $\left\{\phi_{K_j}(x_i), j=\overline{1,m}\right\}$ and (2), the affiliation function of all alternatives x_i, $\left\{i=\overline{1,n}\right\}$ to the summarizing criterion *K* is defined:

$$\phi_K\left(x_i\right)=\sum_{j=1}^{m} w_j \phi_{K_j}\left(x_i\right). \tag{5}$$

3. The alternative, the affiliation function to the summarizing criterion *K* of which gains the maximum value: $\phi\left(x^*\right)=\max\left\{\phi_K\left(x_i\right), i=\overline{1,n}\right\}$.

Selected alternative is the "best" alternative out of *n* number of alternatives, and ranked the first in the list of alternatives ranking for the value of their affiliation function to the summarizing criterion *K*.

4. Functional blocks of researchers' performance assessment system

As noted above, the precise assessment of activity of employees ensures the objectivity and transparency of their management decisions [10]. Based on the proposed technique, the functional scheme of decision support system for the assessment of the activity of scientific employees and their rewarding, promotion and re-deployment based on the evaluation results is illustrated in **Fig. 1.**

Interface ensures the communication between the system and the user. A user can select the following operating modes in the system via the interface:

– submitting the initial information on activity assessment;
– evaluating the activity, obtaining results;
– submitting the rules that shape the knowledge base for appropriate decision support;
– making appropriate management decisions for each employee.

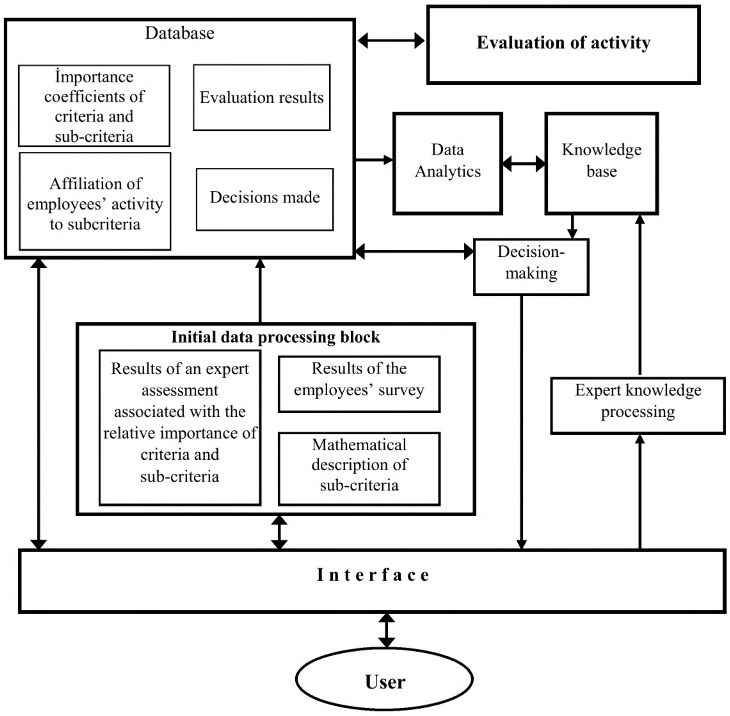

Fig. 1. Functional scheme of decision support system for the assessment of the activity of scientific employees

Initial information processing defines the importance coefficient of criteria and sub-criteria, and generates their mathematical formulation based on the correspondence of employees' activity to sub-criteria.

The mathematical representation of sub-criteria in this block is illustrated in **Table 1** in accordance with the proposed technique. Here, using the 3-level of SQMS, a sequence of mathematical description of the sub-criteria "Participation in the implementation of research" of the criterion "Scientific-theoretical activity", which characterizes the activity of scientific employees.

Table 1
Mathematical description of the sub-criteria "Participation in the implementation of research" characterizing the criteria "Scientific-theoretical activity"

Linguistic variable – granulation of the sub-criteria «Participation in the implementation of research» characterizing the criteria «Scientific-theoretical activity	Linguistic value	Fuzzy subset within the interval [0,1]	Fuzzy number
a) takes an active part in scientific research;	good	[0,9÷1]	0.98
b) takes a part in scientific research;	normal	[0,66÷0,89]	0.70
c) takes part in scientific research partially.	weak	[0,40÷0,65]	0.40

The database (DB) includes the essential data required for the assessment of employees' activity: the affiliation functions of each employee's activity to sub-criteria, the importance coefficients of criteria and sub-criteria, the final estimations of employees' activity (including the results of the periodic assessments), and the decisions related to rewarding, promotion or re-deployment of each employee.

Evaluation of activity implements a mechanism for evaluating employees' activity based on the proposed technique.

The sequence of the evaluation process in this block is described in the following tables in accordance with the proposed technique.

Table 2 builds a two-dimensional fuzzy relation matrix, which represents the degree of correspondence of each worker to the sub-criteria.

Table 2

The membership function of employees' activity to sub-criteria

Alternatives	K						
	K_1			…	K_m		
	k_{11}	…	k_{1L}		k_{m1}	…	k_{mT}
x_1	$\phi_{k_{11}}(x_1)$	…	$\phi_{k_{1L}}(x_1)$	…	$\phi_{k_{m1}}(x_1)$	…	$\phi_{k_{mT}}(x_1)$
…	…	…	…	…	…	…	…
x_i	$\phi_{k_{11}}(x_i)$	…	$\phi_{kL}(x_i)$	…	$\phi_{k_{m1}}(x_i)$	…	$\phi_{k_{mT}}(x_i)$
...	…	…	…	…	…	…	…
x_n	$\phi_{k_{11}}(x_n)$	…	$\phi_{k_{1L}}(x_n)$	…	$\phi_{k_{m1}}(x_n)$	…	$\phi_{k_{mT}}(x_n)$

The next step is to calculate the affiliation function of the employees' activity to the subcriteria in DB based on formula (4) by using the relative importance coefficient of (**Table 3**).

Table 3

The membership function of alternatives to the generalized criterion K

Alternatives	K				
	K_1	…	K_j		K_m
x_1	$\phi_{K_1}(x_1)$	…	$\phi_{K_j}(x_1)$	…	$\phi_{K_m}(x_1)$
…	…	…	…	…	…
x_i	$\phi_{K_1}(x_i)$	…	$\phi_{K_1}(x_i)$	…	$\phi_{K_m}(x_i)$
…	…	...	…	…	…
x_n	$\phi_{K_1}(x_n)$	...	$\phi_{K_j}(x_n)$	…	$\phi_{K_m}(x_n)$

Referring to the results obtained and the relative importance coefficients of the criteria in DB, the final value of the employees' activity is found based on formula (5), and then the results are forwarded to DB.

An employee providing the condition $\phi_K\left(x^*\right)=\max\left\{\phi_K\left(x_i\right), i=\overline{1,n}\right\}$ (n is the number of employees) is the most progressive employee of the institute according to the value of his/her performance corresponding to the criterion x^*, and a list of employees ranked in a decreasing order is obtained similarly.

Data analytics (logical outcome) detects the facts ensuring the results obtained from the evaluation method (including the previous periodical evaluations), and providing the employees' management decisions referring to other data stored in DB.

Knowledge base consists of the rules representing the managerial decisions in accordance with the affiliation of the employees' activity to criteria (or sub-criteria) and summarizing criterion. The first part of the production rules, which are based on expert knowledge and described as "if …, then …", corresponds to the specific fact based on the values of the criterion (or summarizing criterion, sub-criteria) that characterizes the activity for a particular decision. Whereas the "result" represents the management decision appropriate to the same fact.

The rules for staff rewarding are based on the proposed limits related to the amount of the award. It should be noted that the amount of award to be presented to the employees corresponds to the linguistic values on 4 levels, as "very high, high, medium, low". In this case, the rules for awarding can be described as follows:

Rule 1. If $\phi(x_i)\in[0.9,\ 1]$, then the employee may be awarded a "very high" award;

Rule 2. If $\phi(x_i)\in[0.75,0.9)$, then the employee may be awarded a "high" award;

Rule 3. If $\phi(x_i)\in[0,60,\ 0.75)$, then the employee may be awarded a "medium" award;

Rule 4. If $\phi(x_i)\in[0.50,0.60)$, then the employee may be awarded a "low" award;

Rule 5. If $\phi(x_i)\in[0.30,0.50)$, then the employee is not awarded;

Rule 6. If $\phi(x_i)\in[0.00,0.30)$, then the employee must be reviewed.

To support decisions on Staff re-positioning, a profile of the department, where the employee is employed, i. e., the department dealing with scientific research, a department dealing with scientific-practical activities, a serving department (library, multi-media, consulting service, etc.) or education department, should be determined when the regulatory framework of rules base is formed.

Research department of the institute is conditionally denoted by Ss, the department dealing with scientific-practical activities – by Sp, the serving department – by Sx, and the education department – by St. In this case, the following rules may be used to support the re-positioning of employees:

Rule 1. If $\phi_{K_1}(x_i)\in[0.00,\ 0{,}30]$ and $\phi_{K_3}(x_i)\geq 0{,}5$ and $x_i\in S_s$, then the re-positioning of this employee to the scientific-practical department can be reviewed;

Rule 2. If ($\phi_{K_1}(x_i)\in[0.00,\ 0{,}30]$ and $\phi_{k_{33}}(x_i)\geq 0{,}75$ and $x_i\in S_s$), then the re-positioning of this employee to the education department can be reviewed, and so forth.

Here, $\phi_{K_1}(x_i)$ is the affiliation function of the employee to the scientific-theoretical activity criteria, $\phi_{K_3}(x_i)$ – to the scientific-practical activity criteria, and $\phi_{k_{33}}(x_i)\geq 0{,}75$ – to the pedagogical activity criteria.

The formation and perfection of the knowledge base of the system based on the relevant rules is resolved within the framework of the relevant organizational norms, human resource management standards, and under the supervision of the Trade Union in accordance with the protection of the rights and reputations of the employees in the research institution [21, 22].

5. Stages of implementing a decision support system for the management of scientific employees

Based on the methodological approach, a system for the evaluation of the scientific workers' performance working at the Institute of Information Technology of ANAS is developed.

In this regard:

1) a criteria system consisting of 6 criteria characterizing performance of employees is formed:

$$K=\left\{K_m,\ m=\overline{1,6}\right\},$$

where K – generalized criteria of labor activity; K_1 – scientific-theoretical activity; K_2 – scientific-practical activity; K_3 – practical activity; K_4 – supporting activity; K_5 – discipline; K_6 – criterion for increasing professional competence.

Each criterion included into the set of criteria is characterized by a large number of sub-criteria. For example, the sub-criteria characterizing the criterion of scientific-theoretical activity (K_1) are:

– participation in scientific research (k_{11});

– reporting at the institute's workshops (k_{12});

– publishing scientific articles (k_{13});

– supervising doctoral and PhD students (k_{14});

– working with masters (k_{15});

– writing books, brochures, monograph (taking into account scientific and labor capacity) (k_{16});
– reporting at conferences, symposiums and scientific meetings (taking into account levels) (k_{17});
– scientific expertise (writing references to scientific papers) (k_{18}).

Thus, criteria for evaluating the performance of scientific employees are defined as the following subsets:

$$K_1 = \{k_{11}, k_{12}, ..., k_{18}\},$$

$$K_2 = \{k_{21}, k_{22}, ..., k_{25}\},$$

$$K_3 = \{k_{31}, k_{32}, ..., k_{37}\},$$

$$K_4 = \{k_{41}, k_{42}, ..., k_{45}\},$$

$$K_5 = \{k_{51}, k_{52}\},$$

$$K_6 = \{k_{61}, k_{62}, ..., k_{67}\}.$$

2) *To define the relative importance coefficients of criteria and sub-criteria* a 10-grade expert evaluation method is applied. In this regard, 7 tables are developed and submitted to the experts. One of these tables is designed to evaluate the six main criteria that characterize labor activity and the remaining six tables to evaluate the sub-criteria that characterize these criteria.

3) Three-level SQMS is applied for the *mathematical description of the sub-criteria that characterize labor activity.* The approach described in [20] is applied to determine the final fuzzy value based on the individual values defined by the members of an expert group consisting of 5 experts.

Table 4 presents a sequence of mathematical descriptions of the sub-criteria "Participation in the implementation of scientific research (SR)" of the criteria "scientific-theoretical activity" characterizing the labor activity of scientific workers.

Table 4

Mathematical descriptions of sub-criteria "Participation in the implementation of scientific research (SR)" characterizing the criteria "Scientific-theoretical activity"

Linguistic variable – gradation of sub-criteria «Participation in the implementation of scientific research (SR)» characterizing the criteria «scientific-theoretical activity»	Linguistic variable	Fuzzy sub-criteria in interval [0,1]	Fuzzy number
a) Actively participates in the implementation of SR;	good	[0,9÷1]	0.98
b) Participates in the implementation of SR;	normal	[0,66÷0,89]	0.70
c) Partly participates in the implementation of SR.	poor	[0,40÷0,65]	0.40

4) *To collect initial information about the employees' performance*, the "Employee Survey Questionnaire" is drawn up. The survey questionnaire describes the employee's first name, last name, department, activity criterion, and the sub-criteria that characterize these criteria, and the gradation of each of them.

Each employee fills in a questionnaire by specifying the gradation of the sub-criteria he/she considers appropriate for his/her activity. Thus, he/she indirectly participates in the labor activity assessment process and solves the problem of "who evaluates an employee?" which is one of the most important methodological problems in the development of the evaluation system. This approach is called *self-assessment* and allows each employee to express honest and essential information about his/her labor activity. Another advantage of self-assessment is that it allows each employee to analyze himself/herself which encourages him/her to use own abilities and skills more efficiently. The information source provided to the "Employee Survey Questionnaire" approved by the head of the Institute and the head of the department is the primary information source for the evaluation system to be developed.

5) Relevant software and a computer system for the evaluation of scientific workers' performance are developed.

The information is submitted to the database of the system on the following forms:

1) list of departments of the institute;
2) list of employees by departments;
3) list of criteria characterizing the labor activity;
4) list of sub-criteria characterizing the labor activity;
5) list of gradations of sub-criteria and fuzzy values of each gradation in the interval [0,1];
6) list of experts;
7) 10-grade expert estimates to determine the importance coefficients of criteria;
8) 10-grade expert estimates to determine the importance coefficients of sub-criteria;
9) survey questionnaire data;
10) relative importance coefficients of criteria;
11) relative importance coefficients of sub-criteria.

Based on the submitted initial data, the value of each employee's labor activity is determined, and this information is stored in the database.

At the next stage, a list of employees ranked based on the values of their labor activity is developed. It should be noted that the ranked list is possible to be developed on the institute (**Fig. 2**), on separate departments (**Fig. 3**) and also on criteria (and sub-criteria).

DB review enables the review and update of departments, data based on surveys based on surveys, chapters, employees, criteria, sub-criteria, grades, experts, expert estimates of criteria, expert estimates of sub-criteria, and review and update of data based on Survey Questionnaire.

The data can be submitted to the database based on the questionnaire by selecting the "Employee's Performance Evaluation" mode, and the input data can be modified and deleted.

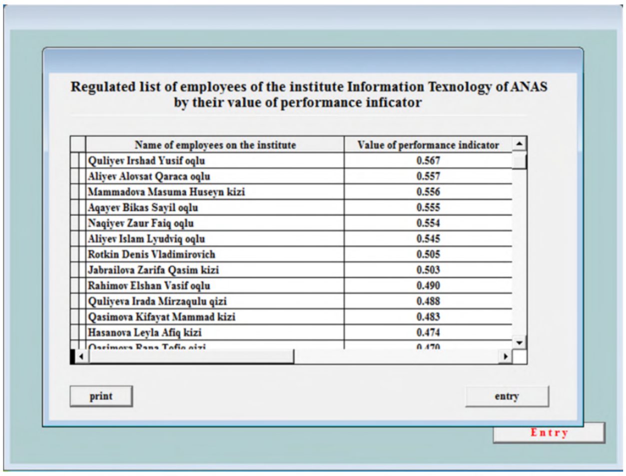

Fig. 2. Value of performance indicator of employees on the Institute (regulated list)

The survey data of each employee can be viewed based on the form.

The following three different calculation operations are performed in the system calculation block, and the obtained results are stored in the database:

– Referring to the results of 10-grade evaluation of the criteria of 17 experts stored in DB, their relative importance coefficients are calculated, and the results are stored in DB;

– Referring to the results of 10-grade evaluation of the sub-criteria of 17 experts stored in DB, their relative importance coefficients are calculated, and the results are stored in DVB;

– Based on the information on the employee's labor activity submitted to the DB based on the survey questionnaire, "Calculation of the value of the labor activity" operation is performed in the calculation block, and the results are stored in DB.

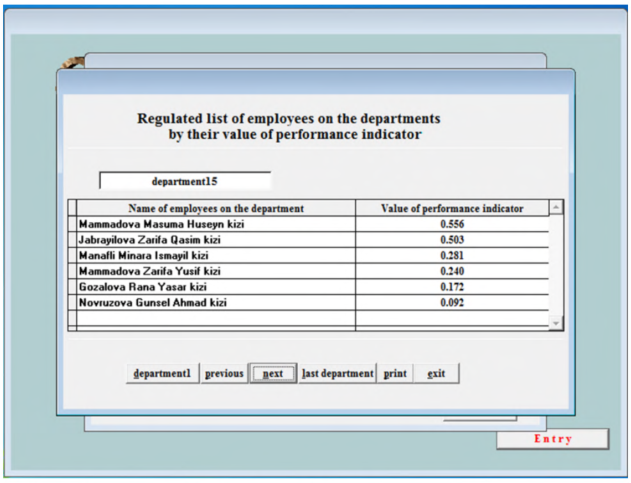

Fig. 3. Value of performance indicator of employees on departments (regulated list)

At this stage, the sequence of the data processing and the final evaluation of the labor activity of employees are executed on the following algorithm.

The fuzzy values corresponding to the gradations of the sub-criteria specified in accordance with the "Employee Survey Questionnaire" are selected from the certain table and represented in a new table in the 2-dimensional fuzzy relation matrix in front of the name of the corresponding employee.

The value mentioned refers to the extent to which the relevant employee corresponds to that sub-criteria (**Table 5**).

Table 5

Membership function of the employees' performance to the sub-criteria

No.	List of employees	Notation keys	**K**							
			K_1				…		K_6	
			k_{11}	k_{12}	…	k_{18}	…	k_{61}	…	k_{67}
1	Abbasova M. Z.	x_1	$\phi_{k_{11}}(x_1)$	$\phi_{k_{12}}(x_1)$	…	$\phi_{k_{18}}(x_1)$	…	$\phi_{k_{61}}(x_1)$	…	$\phi_{k_{67}}(x_1)$
2	Bayramov N. L.	x_2	$\phi_{k_{11}}(x_2)$	$\phi_{k_{12}}(x_2)$	…	$\phi_{k_{18}}(x_2)$	…	$\phi_{k_{61}}(x_2)$	…	$\phi_{k_{67}}(x_2)$
	…	…	…	…	…	…	…	…	…	
N.	Aliyeva L. H.	x_n	$\phi_{k_{11}}(x_n)$	$\phi_{k_{12}}(x_n)$	…	$\phi_{k_{18}}(x_n)$	…	$\phi_{k_{61}}(x_n)$	…	$\phi_{k_{67}}(x_n)$

The next step is to calculate the membership function of the employee's performance based on the formula (4) by using the relative importance coefficients of the sub-criteria in DB (**Table 6**).

Table 6

Membership function of the employee's performance to the criteria

No.	List of employees	Notation keys	**K**					
			K_1	K_2	K_3	K_4	K_5	K_6
1	Abbasova M. Z.	x_1	$\phi_{K_1}(x_1)$	$\phi_{K_2}(x_1)$	$\phi_{K_3}(x_1)$	$\phi_{K_4}(x_1)$	$\phi_{K_5}(x_1)$	$\phi_{K_6}(x_1)$
2	Bayramov N. L.	x_2	$\phi_{K_1}(x_2)$	$\phi_{K_2}(x_2)$	$\phi_{K_3}(x_2)$	$\phi_{K_4}(x_2)$	$\phi_{K_5}(x_2)$	$\phi_{K_6}(x_2)$
	…	…	…	…	…	…	…	…
N.	Aliyeva L. H.	x_n	$\phi_{K_1}(x_n)$	$\phi_{K_2}(x_n)$	$\phi_{K_3}(x_n)$	$\phi_{K_4}(x_n)$	$\phi_{K_5}(x_n)$	$\phi_{K_6}(x_n)$

Based on the results obtained and the relative importance coefficients of the criteria in DB, the final value of the employees' labor activity is found based on the formula (5), and the results are uploaded to on the DB.

The employee ensuring the condition $\phi_K\left(x^*\right)=\max\left\{\phi_K\left(x_i\right), i=\overline{1,n}\right\}$ (n is the number of employees) in accordance with the alternative x^* is the most advanced employee at the institute, and in this way, the list of employees' performance ranking is obtained.

6. Results and Discussion

Solution of the development of the decision support system for the management of scientific employees and the evaluation of their labor activity decisions was implemented in three stages. At the first stage, the scientific-theoretical basis of the system to be developed was created. It was shown that the work of employees engaged in scientific activity is determined by a great number of criteria. These criteria are often qualitative, indefinite and fuzzy. This feature requires referring to the expert knowledge and to the linguistic expressions of our natural language as the measurement metrics for the evaluation of labor activity. Thus, the issue is characterized by a multi-criterion assessment problem formed in a fuzzy environment, and a fuzzy relation model is proposed for its solution. The criterion that characterizes the work of employees involved in scientific activities are hierarchic and their importance (both criteria and their sub criteria) are diverse. Thus, taking into account this, additive aggregation-based evaluation technique was proposed. The definition of the relative importance coefficients of input data, that is criteria (and their sub-criteria), and mathematical description methods of criteria are proposed. Proposed methodological approach:

– evaluates the labor activity of employees engaged in scientific activity univocally taking into account all indicators characterizing their activity and importance of these indicators;

– ensures objective and transparent management decisions and employees' satisfaction by fairly evaluating their labor activity.

At the second stage, the evaluation based on the proposed technique and referring to the evaluation results, the principles of projecting the management decision support system are performed. Functioning principles of the system, the working principles of its blocks and their interaction are shown. The system capabilities are as follows:

– univocally evaluates and ranks the outcome of each employee's labor activity for each sub-criterion, criterion and generalization criterion (labor activity value);

– identifies the most advanced (or passive) employee by each department (laboratory, group, etc.);

– identifies the most advanced (or passive) department (laboratory, group, etc.) by the institute (research center, organization etc.);

– identifies the most advanced (or passive) employee at the institute.

Referring to the assessment results, processing of employees' management decisions took place in the system knowledge base. Processing of employees' management decisions based on the knowledge production model was described in the examples of the issues regarding the awarding, re-recruitment and judgment of employees. And relevant rules constituting the knowledge base were developed.

At the third stage, the implementation phases of the decision support system for the management of scientific employees were given. This experiment was presented as an example of the evaluation system of the scientific employees' activity of the Institute of Information Technology of ANAS. In this regard, followings were implemented:

– a system of criteria characterizing the labor activity of employees was formed;

– relative importance coefficients of criteria and sub-criteria were determined;

– a mathematical description of sub-criteria characterizing the labor activity was presented;

– self-assessment method was used to obtain initial information about the employees' activity;

– a relevant software product was developed based on the proposed evaluation technique.

As a result of implementing the periodic assessment (for example, semi-annual), the system can designate the dynamics of each employee for a particular criterion (or overall activity dynamics). This is, of course, very valuable information in managing employees.

The scientific and functional principles of the decision support system can also be used for other issues of human resource management (e. g. recruitment) that require intellectual support.

Thus, proposed scientific-methodological approach can be used not only to evaluate the scientific employees, but also to improve the management decisions and the evaluation of performance of other employees. These employees may work for government and commercial organizations, enterprises and offices. The use of such a system may assist the decision makers, managers, and other specialists in relevant fields dealing with employees' management.

The proposed approach requires deep and systematic study of the human resources, and the consideration of all criteria and sub-criteria characterizing their labor activity. On the other hand, inclusion or exclusion of any criterion (or sub-criterion) causes substantial changes in the implementation phase of the system. It may change the importance of others and cause for making amendments in the survey questionnaire for initial data collection. All this entails making proper changes to the software product, as well. One of the challenges of the system difficult is related to building a knowledge base, the acquisition of knowledge of analysts, and establishing decision-making rules.

7. Conclusion

Scientifically justified decisions regarding the management of scientific employees is crucial. Improvement of this process necessitates the introduction of intelligent technology. In this article, the scientific-theoretical and functional principles of developing an intelligent decision support system for the management of scientific employees were developed. To achieve this result, the followings were implemented:

– characteristics of the assessment of activity of scientific employees was defined, and fuzzy relation model as a multi-criteria ranking problem formed in an uncertain environment was proposed;

– problem solution technique based on the additive aggregation method was developed, taking into account the hierarchical structure of criteria and diversity of their importance;

– architectural principles and functional structure of the decision support system for employees' management were developed by referring to the evaluation results;

– results of the specific product generated in a certain environment by referring to the proposed scientific and functional principles were described. The decision support system for employees' management was implemented in stages.

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METHODS FOR FUZZY DEMAND ASSESSMENT FOR IT SPECIALTIES

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Abstract

The rapid development of information technologies and their penetration into various spheres of human activity cause a sharply increased demand for IT specialists, in many countries of the world far exceeding the supply on them. High rates of technological transformation contribute to the diversification of the IT segment of the labor market, on the one hand, stimulate the disappearance of some and the emergence of new IT specialties, on the other. This creates a discrepancy between the structure of IT-related education and the labor market demand for IT specialists of the required profile and determines the relevance of developing methods for assessing the demand for IT specialties.

This article is devoted to the study and solution of the problem of identifying the demand for IT specialties in the absence of accurate and complete information about the situation in the IT market segment. For the assessment of IT specialties and their ranking by the degree of demand in the labor market, the tasks of making individual and group decisions in the context of fuzzy initial information are formulated and solved. The methodological basis of the tasks posed is multi-criteria decision support methods based on fuzzy relations of expert preferences.

The proposed approach as a mathematical tool for minimizing the structural imbalance of supply and demand for IT specialties is one of the components of the system of intellectual management of the labor market of IT specialists. The latter is designed to support the adoption of scientifically based management decisions to eliminate the mismatch of supply and demand in the IT segment of the labor market in professional, quantitative and qualitative sections.

Keywords: IT specialties, demand, supply, labor market, fuzzy source information, decision making.

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1. Introduction

Currently, the special role of information technology (IT) in the development of both the global and national economies, stimulating the growth of productivity, competitiveness and innovation potential of industries and enterprises is beyond doubt. Large-scale digitalization and the transformation of information into a global resource have led to a sharply increased demand for IT professionals in the labor market, which in many countries around the world now far exceeds the supply for them. So, according to [1–3] in Europe, the demand for IT specialists is growing by about 3–4 % annually and is ahead of their supply. According to experts, the number of IT vacancies by 2025 may increase from 750 thousand to 1 million compared to 274 thousand in 2013. The shortage of IT specialists observed in almost all EU countries occurs against the background of a reduction in the number of people receiving the highest IT profile in Europe, as well as engineering and science education. Probably many of these potential vacancies will remain unfilled if measures are not taken to attract young people to IT education, retraining, on the one hand, to systematically update the structure of the IT professions and specialties, and accordingly, training programs, on the other hand. Growth in demand for IT professionals and their insufficient supply are also observed in such developed countries as the USA and Canada [4–6]. The CIS countries, including Azerbaijan, which are actively integrating into the global information society, also faced the problem of mismatch of supply and demand for IT specialists [7–9].

Analysis of the demand in the IT segment of the labor market in Azerbaijan, the calculation of the total number of IT specialists and their supply by the IT profile education system, as well as the number of IT specialists required to cover replacement, revealed a significant imbalance of these indicators [10–12]. The shortage of IT specialists is mainly covered by the influx into the IT industry of workers whose basic specialization does not coincide with the professional structure of their position (for example, representatives of professions that are potentially close to IT or are completely unrelated to IT work as an IT specialist this industry).

Technological transformation of the IT sphere requires continuous updating of the professional knowledge and skills (competencies) of IT specialists. The opening of new jobs demanded by the digital economy, the expansion of digital labor markets and the growing number of virtual organizations determine the need for IT professionals with new professional competencies [13]. This causes the disappearance of some IT professions and specializations due to the obsolescence of a number of professional competencies and the emergence of others. However, the inert education system does not have time to respond to rapid technological changes in a timely manner, continuing to produce IT specialists, whose professional knowledge and skills do not correlate well with current and future labor market needs. At the same time, the IT industry has to constantly adapt to their rapidly changing requirements in order to maintain competitiveness in the global, national and local markets. All this contributes to the increasing mismatch between the IT-specific education system and the labor market and leads to a situation where, for a number of new IT specialties demanded in the labor market, not one university in the country trains specialists.

Today, the problem of identifying the structure and needs of the labor market in the context of professions and specialties is one of the most relevant and insufficiently studied in many countries, including Azerbaijan. It is not by chance that the issues of identifying supply and demand for various professions and specialties, reorienting the education system to the needs of the labor market in the country as priorities are reflected in a number of political documents [14–17]. They prioritized the need to solve such important tasks as identifying supply and demand for various professions and specialties; improving the training of personnel competitive in the labor market; reorientation of the education system to the needs of the labor market, i.e. on employers 'requirements for graduates' knowledge and skills, etc. In this context, the study of the structure of IT specialties from the standpoint of their relevance in the labor market is a rather important task.

2. Approaches to demand assessment in the IT segment of the labor market in the context of IT occupations and specialties

The aim of this article is development of methods for demand (necessaty) assessment for IT professions and specialties, which allow identifying the degree of demand for labor in the labor market, ranking them in order of increasing (decreasing) significance, determining the level of structural imbalance of supply and demand in the IT market segment labor.

Problem statement. There are a predetermined number of IT professions and specialties identified by examining the structure of the IT segment of the labor market. It is required to assess the need for IT specialties and their ranking (streamlining) from the most promising to low demand from the positions of demand in the labor market. Let's note that the ordering of the list of specialties takes into account the demand for a particular IT specialty as a whole, and not the likelihood of employment of each IT specialist.

The problem of assessing and selecting the most demanded IT labor specialties in the labor market falls under the category of weakly structured tasks that traditionally boil down to making decisions with fuzzy initial information [18, 19]. This is due to the "soft" nature of the labor market itself as an object of management, as well as the formation of demand and supply for IT professions and specialties under the influence of a variety of uncertainties – incompleteness, inaccuracy, ambiguity of data. The lack of complete statistical information about the demand and supply of IT specialties, the difficulty of acquiring reliable information about the labor market status of IT specialists, the ambiguity of the system of indicators characterizing demand and supply, their quantitative and qualitative nature, high dynamism of the IT industry lead to an increase in the uncertainty of the initial information and reduce the effectiveness of management decisions made by traditional methods [20].

The task of demand assessment for IT specialties as weakly structured is in selection of the most demanded from a variety of IT specialties and is based on using the preferences of experts or decision makers. Experts are involved in the process of evaluating IT specialties (alternatives) for a set of attributes that form the degree of demand for a specialty in the market, and express preference relations for each of them, and the task of assessing the need for IT specialties can be reduced to streamlining alternatives with fuzzy initial information [18].

To assess the demand for IT specialties and their ordering according to the degree of demand in the IT segment of the labor market, methods of fuzzy multi-criteria adoption of individual and group expert decisions on the selection of priority IT specialties based on a fuzzy relational knowledge representation model have been proposed [21]. The practical implementation of methods for assessing the need for IT specialties was carried out on the basis of the list of the latter, formed during the study.

3. The method of fuzzy multi-criteria adoption of individual expert decisions on the choice of priority IT specialties

Let's there are many IT specialties that are subject to assessment and ranking in terms of their relevance in the labor market. Formally, this set can be described as a set of alternatives

$$X=\{x_1, x_2, ..., x_n\}=\{x_i,\ i=\overline{1,n}\},$$

each of which is characterized by a set of criteria

$$K=\{k_1, k_2, ..., k_m\}=\{k_j,\ j=\overline{1,m}\}.$$

The task of assessing the need for IT specialties with the greatest demand in the labor market is reduced to the task of choosing the best alternatives among the many assessed, taking into account the attitude of preferences of an individual expert.

The degree of satisfaction of the set of alternatives X to the criteria K

$$K=\{k_j,\ j=\overline{1,m}\}$$

is determined by the set of membership functions

$$\mu_{k_j}(x_i): X\times K \to [0,1],\quad j=\overline{1,m}, \tag{1}$$

where $\mu_{k_j}(x_i)$ expresses the satisfaction degree of the alternative x_i by criterion k_j.

The choice of the best (non-dominated) alternative is reduced to a multicriteria problem of fuzzy mathematical programming, for the solution of which the Generalized Bellman-Zadeh approach [18, 22] is applicable. Moreover, the degree of belonging of alternatives to a fuzzy solution of the problem is equal to the minimum of these digits for all the criteria $K=\{k_j, j=\overline{1,m}\}$, $\Omega=k_1\cap k_2\cap...\cap k_m$:

$$\mu_\Omega(x_i)=\min_{\underline{j=1,m}}\mu_{k_j}(x_i),\quad i=\overline{1,n}. \tag{2}$$

As the best (effective) alternative is selected x^*, which has the highest value of the membership function:

$$\mu_\Omega(x^*)=\max_{\underline{j=1,m}}\mu_{k_j},\quad (x_i)=\max_{\underline{i=1,n}}\mu_\Omega(x_i). \tag{3}$$

This means that the IT specialty corresponding to this alternative is most in demand in the labor market.

In accordance with the values of the membership functions, expressing the degree of satisfaction of alternatives to the criteria, IT specializations are streamlined according to the degree of their demand in the labor market.

4. The method of fuzzy multi-criteria group decision making on the choice of priority IT specialties

In this case, the task of assessing the demand for IT specialties is reduced to the problem of choosing among the many evaluated alternatives the best, taking into account the relations of preferences of several experts. The satisfaction degree of the set of alternatives X to the set of criteria K is determined by the set of membership functions

$$\phi_{k_j}(x_i): X \times K \to [0,1]. \tag{4}$$

Set of experts G is formed by the decision maker, who is guided by his own opinion on the level of their competence. For each of the experts $g \to G$, a fuzzy preference relation is defined on the set of alternatives X, i. e. membership function of the form ψ: $X \times X \times G \to [0,1]$. Naturally, in the process of multi-criteria evaluation of alternatives, experts proceed from their own preference relations. The value $\psi(x_i, x_j, g)$ is interpreted as the degree of preference of the alternative x_i to the alternative x_j, through the prism of the preferences of the expert g and is determined as follows:

$$\psi(x_i, x_j, g) = \begin{cases} 1 - \left[\phi(x_j, g) - \phi(x_i, g)\right], & \text{if } \phi(x_j, g) \geq \phi(x_i, g), \\ 1, & \text{if } \phi(x_j, g) \leq \phi(x_i, g), \end{cases} \tag{5}$$

where

$$\varphi(x_i, g) = \min\left\{\varphi_{k_j}(x_i, g),\ j = \overline{1, m}\right\}.$$

Using the expression (5) of each expert, a matrix of unclear preference relations of alternatives is determined.

On the other hand, the decision maker unequally evaluates the competence of experts invited by them to assess alternatives. This factor is reflected by the coefficient of competence of experts: $\gamma(g) \to [0,1]$, taking into account which from the expression

$$\nu(g_1, g_2) = \begin{cases} 1 - \left[\gamma(g_2) - \gamma(g_1)\right], & \text{if } \gamma(g_2) \geq \gamma(g_1), \\ 1, & \text{if } \gamma(g_2) \leq \gamma(g_1), \end{cases} \tag{6}$$

by ν: $G \times G \to [0,1]$ is determined – fuzzy relation of expert competence. The value $v(g_1, g_2)$ is understood as the degree to which, in the opinion of the decision maker, the expert g_1 is more competent than the expert g_2.

After this, the problem reduces to a rational choice of alternatives from the set X, taking into account the information described above. According to [22], $\psi^{n.d.}(x_i, g)$ – defined as a fuzzy subset of non-dominated alternatives, corresponding to a fuzzy preference relation $\psi(x_i, x_j, g)$) with fixed $g \in G$:

$$\psi^{n.d.}(x_i, g) = 1 - \sup_{x_j \in X}\left[\psi(x_j, x_i, g) - \psi(x_i, x_j, g)\right]. \tag{7}$$

The alternatives that give the largest possible value of the membership function $\psi^{n.d.}(x_i, g)$ on the set X coincide with the individual solution of the g-th expert.

Further, the fuzzy relation $v(g_1, g_2)$ is generalized to the class of fuzzy subsets of the set G. The induced (generalized) fuzzy relation on the set X is defined as follows:

$$\eta(x_i, x_j) = \sup_{g_1, g_2 \in G} \min\left\{\psi^{n.d.}(x_i, g_1), \psi^{n.d.}(x_j, g_2), v(g_1, g_2)\right\}. \tag{8}$$

This fuzzy preference relation is the result of a “convolution” of a family of fuzzy relations $\psi(x_i, x_j, g)$ into a single resulting fuzzy preference relation, taking into account information about the competence of experts in a given subject area.

Induced preference relations on the set X make it possible to proceed to the problem of choosing alternatives with a single preference relation by defining the corresponding set of non-dominated alternatives.

$$\tilde{\eta}^{n.d.}(x_i) = 1 - \sup_{x_j \in X}\left[\eta(x_j, x_i) - \eta(x_i, x_j)\right]. \tag{9}$$

Finally, from the expression

$$\eta^{n.d.}(x_i) = \min\left\{\tilde{\eta}^{n.d.}(x_i),\ \eta(x_i, x_j)\right\} \tag{10}$$

the corrected fuzzy set of non-dominated alternatives is determined and an alternative is chosen that delivers the maximum of the $\eta^{n.d.}(x)$ function

$$\eta^{n.d.}(x) = \sup_{x_j \in X} \eta(x_i), \tag{11}$$

which is the most effective alternative. The selected alternative is the resulting group choice decision and coincides with one of the individual decisions.

5. An empirical experiment on the fuzzy assessment of the demand for IT specialties

For the practical implementation of the task of assessing the demand for IT professions and specialties used: a list of IT professions and specialties, based on the results of monitoring the IT segment of the labor market [9, 20]; data on IT professions and specialties, which are taught in the education system of Azerbaijan; codifier of professions and specialties ISCO-08; statistics from the State Employment Service; vacancy announcements in open Internet resources; employers' applications for filling vacancies on the websites of recruitment agencies. As a result, the entire list of IT specialties is combined into 14 integrated groups of IT specialties.

Great importance has the formation of the selection criteria for evaluating the latter for comparison of IT specialties (alternatives). These criteria, on the one hand, should characterize IT specialties from the standpoint of the ratio of supply and demand in the market, on the other hand, should allow them to be ranked, i. e. ordering in ascending or descending order. In this case, the criteria characterizing the alternatives can be both quantitative (for example, wages for the specialty being assessed) and qualitative (for example, the imbalance of supply and demand).

For selection of criteria and scales for assessing priority IT specialties, discussions were held with leading experts-experts of the Institute of Information Technologies of the National Academy of Sciences of Azerbaijan (IIT ANAS), the Ministry of Education, IT industry and a list of the latter was compiled. As criteria applied to the assessment of IT specialties, the following are highlighted:

1. The degree of priority of the IT specialty, both in the context of the industry, and in other sectors of the economy (k_1).
2. The imbalance of supply and demand in the context of IT specialties (k_2).
3. Wages in the assessed IT specialty (k_3).
4. The demand for the assessed IT specialties from the position of employment (IT specialists with a certain specialization are required to fill the declared vacancies) (k_4).
5. Proposal for the assessed IT specialties from the position of employment (IT specialists with a specific specialization applying for the stated vacancies) (k_5).

The procedure for assessing and streamlining alternatives (IT specialties) is as follows: experts are provided with a full list of alternatives to be assessed, as well as criteria, their terms (fuzzy grading scales) and the range of the latter. The task of the experts is in assessing each IT specialty on a set of criteria. When assigning the membership function for each criterion, on the one hand, it is necessary to assess the alternative for all criteria (by their set), on the other hand, to take into account the importance of the alternative for each individual criterion. When determining the membership functions $\phi_{k_j}(x_i)$, the criteria scale is used, which, regardless of the nature of the latter (qualitative or quantitative), determines their values in the interval [0,1]. Fuzzy assessment of criteria has convenient and understandable for experts qualitative gradations and their fuzzy correspondences, which take on the value from the area (range) of changes in terms (**Table 1**).

Table 1

The membership functions of fuzzy sets of verbal gradations of the linguistic variable "imbalance of supply and demand for IT specialties

The name of the criterion (linguistic variable)	Terms – fuzzy estimates of the linguistic variable gradations "imbalance of supply and demand for IT specialties"	Range of change of membership functions
Imbalance of supply and demand for IT specialties	Optimal (normative) imbalance	[0,8;1]
	Minimal imbalance	[0,6;0,8)
	Allowable imbalance	[0,4;0,6)
	Critical Imbalance	[0,2;0,4)
	Total imbalance	[0;0,2)

Taking into account the cumbersome fuzzy logic calculations for the full set of alternatives, the following is a practical implementation of the group decision-making method for their evaluation and ranking using a small dimension as an example.

Let $X=\{T_1, T_2, T_3, T_4, T_5, T_6\}$ – a given set of alternatives – IT professions and specialties. $K=\{k_1, k_2, k_3, k_4, k_5\}$ – criteria by which the alternatives are assessed. In this case, the following were selected as IT occupations and specialties: T_1 – programmer, T_2 – system analyst, T_3 – information security specialist, T_4 – database administrator, T_5 – IT researcher, T_6 – network engineer.

The selection process involves 3 experts. The coefficients of expert competence in accordance with the preferences of the decision maker are expressed in the following values:

$$\gamma(G_1)=0.9,\ \gamma(G_2)=1,\ \gamma(G_3)=0.9.$$

Tables 2–4 present the results of logical calculations of the degrees of satisfaction of a set of alternatives to a set of criteria according to the estimates of each of the three experts.

Table 2

Satisfaction degrees of the set of alternatives to the set of criteria according to the estimates of the first expert G_1

X \ *K*	k_1	k_2	k_3	k_4	k_5	$\min\phi_{kj}(T_i)$	$\max\varphi(T_i)$
T_1	0	0.54	0.52	0.62	0.82	0	–
T_2	0	0.74	0.24	0	0.66	0	–
T_3	0.12	0.12	0.50	0.62	0.64	0.12	0.34
T_4	0.34	0.40	0.42	0.56	0.52	0.34	–
T_5	0.32	0.54	0.56	0.62	0.82	0.32	–
T_6	0.24	0.32	0.46	0.54	0.52	0.24	–

Table 3

Satisfaction degrees of the set of alternatives to the set of criteria according to the estimates of the second expert G_2

X \ K	k_1	k_2	k_3	k_4	k_5	$\min\phi_{kj}(T_i)$	$\max\varphi(T_i)$
T_1	0.34	0.46	0.32	0.52	0.46	0.32	–
T_2	0.8	0.24	0.44	0.72	0.46	0.08	–
T_3	0.36	0.32	0.34	0.44	0.32	0.32	0.32
T_4	0.34	0.06	0.04	0.14	0.22	0.04	–
T_5	0.36	0.32	0.26	0.26	0.22	0.22	–
T_6	0.64	0.44	0.24	0.42	0.36	0.24	–

Table 4

Satisfaction degrees of the set of alternatives to the set of criteria according to the estimates of the third expert G_3

X \ K	k_1	k_2	k_3	k_4	k_5	$\min\phi_{kj}(T_i)$	$\max\varphi(T_i)$
T_1	0.44	0.32	0.40	0.70	0.60	0.32	–
T_2	0.20	0.30	0.10	0.40	0.50	0.10	–
T_3	0.20	0.30	0.40	0.50	0.20	0.20	–
T_4	0.10	0.10	0.16	0.30	0.04	0.04	–
T_5	0.70	0.50	0.70	0.70	0.70	0.50	0.50
T_6	0.50	0.50	0.60	0.70	0.36	0.36	–

Here, the membership functions of the solution are determined by the intersection of the satisfaction degree of alternatives to the criteria, i. e.

$$\phi(T_i) = \min_{T_i \in X} \left\{ \phi_{kj}(T_i),\ j = \overline{1,5} \right\}.$$

Alternatives satisfying the condition

$$\max_{T_i \in} \phi(T_i) = \max_{T_i \in} \min \left\{ \phi_{kj}(T_i),\ j = \overline{1,5} \right\},$$

are the most effective solutions (popular IT specialties). In this case, the most effective solutions according to the estimates of the first expert G_1 are the alternative T_4, according to the estimates of the second expert G_2 – alternatives T_1 and T_3, according to the estimates of the third expert G_3 – alternative T_5.

On the basis of formula (5), a comparison of alternatives is carried out, the results of which for each of the experts are described by the matrices of the non-strict preference, presented in **Tables 5–7**.

Table 5

Relationships of non-strict preferences according to expert G_1

T_i \ T_j	T_1	T_2	T_3	T_4	T_5	T_6
T_1	1	1	0.88	0.66	0.68	0.76
T_2	1	1	0.88	0.66	0.68	0.76
T_3	1	1	1	0.78	0.8	0.88
T_4	1	1	1	1	1	1
T_5	1	1	1	0.98	1	1
T_6	1	1	1	0.9	0.92	1

Table 6

Relationships of non-strict preferences according to expert G_2

T_i \ T_j	T_1	T_2	T_3	T_4	T_5	T_6
T_1	1	1	1	1	1	1
T_2	0.76	1	0.76	1	0.86	0.84
T_3	1	1	1	1	1	1
T_4	0.72	0.96	0.72	1	0.82	0.80
T_5	0.9	1	0.9	1	1	0.98
T_6	0.92	1	0.92	1	1	1

Table 7

Relationships of non-strict preferences according to expert G_3

T_i \ T_j	T_1	T_2	T_3	T_4	T_5	T_6
T_1	1	1	1	1	0.82	0.96
T_2	0.78	1	0.9	1	0.6	0.74
T_3	0.88	1	1	1	0.7	0.84
T_4	0.72	0.94	0.84	1	0.54	0.68
T_5	1	1	1	1	1	1
T_6	1	1	1	1	0.85	1

Competence of experts is described using the fuzzy relationship matrix "not less important", calculated by the formula (6):

$$\begin{pmatrix} 1 & 0.9 & 1 \\ 1 & 1 & 1 \\ 1 & 0.9 & 1 \end{pmatrix}.$$

The set of non-dominated alternatives, reflecting respectively the ratio of preferences of each expert, is presented in the form of a matrix:

$$\begin{pmatrix} 1 & 1 & 1 & 1 & 0.98 & 0.9 \\ 0.78 & 1 & 0.9 & 1 & 0.9 & 0.92 \\ 0.88 & 1 & 1 & 1 & 1 & 0.86 \end{pmatrix}.$$

Further, using the expression (8)

$$\eta(T_i,T_j) = \sup_{g_1,g_2\in G}\min\left\{\phi^{n.d.}(T_i,g_1),\ \phi^{n.d.}(T_j,g_2),\ \nu(g_1,g_2)\right\},$$

let's obtain the matrix of the induced preference relation on the set of alternatives (**Table 8**).

Table 8

Matrix of induced preference relationship on the set of alternatives

T_i \ T_j	T_1	T_2	T_3	T_4	T_5	T_6
T_1	1	0.76	1	1	1	1
T_2	0.76	0.76	0.76	0.76	0.76	0.76
T_3	1	0.76	1	1	1	0.92
T_4	1	0.36	0.9	1	1	0.9
T_5	0.9	0.76	0.9	0.98	1	0.9
T_6	0.92	0.76	0.92	0.92	0.92	0.92

The expression (9) allows to select an unadjusted set of non-dominated alternatives:

$$\tilde{\eta}^{n.d.}(T_i) = 1 - \sup_{T_j\in X}\left[\eta(T_j,T_i) - \eta(T_i,T_j)\right],$$

$$\tilde{\eta}^{n.d.}(T_i) = \frac{T_1 \quad T_2 \quad T_3 \quad T_4 \quad T_5 \quad T_6}{1 \quad 1 \quad 1 \quad 0{,}9 \quad 0{,}9 \quad 1}.$$

Finally, using formulas (10), (11), the corrected fuzzy set of non-dominated alternatives is determined and an alternative is chosen that delivers the maximum of the function $\eta^{n.d}(x)$:

$$\eta^{n.d.}(T_i) = \min\left\{\tilde{\eta}^{n.d.}(T_i),\ \eta(T_i,T_j);\quad \eta^{n.d.}(T) = \max \eta^{n.d}(T_i)\right\},$$

$$\eta^{n.d.}(T) = \frac{T_1 \quad T_2 \quad T_3 \quad T_4 \quad T_5 \quad T_6}{1 \quad 0{,}76 \quad 1 \quad 0{,}9 \quad 0{,}9 \quad 0{,}92}.$$

The obtained results allow to conclude that the choice of alternatives T_1 and T_3 is rational in this case. This means that the specialties "programmer" and "information security" are the most demanded in the labor market. By priority, alternatives are ranked in the following order: T_1, T_3, T_6, T_4, T_5, T_2. In accordance with this ranking, let's obtain the following ordering of IT professions and specialties:

1. Programmer.
2. Information security specialist.

3. Network engineer.
4. Database administrator.
5. IT researcher.
6. System analyst.

Expert assessment and fuzzy logical calculations using the proposed methods for all 14 evaluated groups of IT specialties allowed the latter to be streamlined according to the degree of their relevance in the labor market:

1. Programmer.
2. Programmer-developer (Web, SQL, JavaScript, Linux, etc.).
3. Information security specialist.
4. Information systems specialist.
5. Network engineer.
6. System administrator.
7. Database administrator.
8. IT manager.
9. Sales and marketing manager of solutions and complex technical systems.
10. Consultant for the implementation of IT solutions.
11. IT researcher.
12. Electronic engineer.
13. System analyst.
14. System architect.

Testing the effectiveness of the proposed approach was carried out by comparative analysis with the results of monitoring supply and demand for IT specialties [9, 20], as well as with the professional orientation of IT vacancies announced in open Internet resources on the websites of employment services and recruiting agencies [23–26]. The analysis of the vacancy dynamics in the above mentioned IT specialties confirms by 80–85 % the obtained ordering, i. e. IT specialties that fall into the category of priority according to the proposed assessment methodology are also the most demanded in the labor market.

6. Conclusions

Identifying the demand for IT professions and specialties that are most in demand in the labor market makes it possible to determine the current and forecast the future structure and volume of supply for them. This factor should be taken into account when determining the reference figures for admission of students to universities in the context of IT specialties, which are often not sufficiently substantiated from the standpoint of supply and demand in the labor market.

The methodical approach proposed in the article for assessing the demand for IT professions and specialties can support various users (employees of government bodies responsible for labor market policy and training, educational institutions, employers, individuals, employment counselors, HR departments, applicants) in obtaining scientifically based information about the real needs of the IT segment of the labor market and, accordingly, in making scientifically based decisions.

The methods of minimizing the structural imbalance of supply and demand for IT specialties form the mathematical basis of one of the components of the IT specialists' intellectual labor market system designed at IIT ANAS. The purpose of the system is in support of the adoption of scientifically based management decisions to eliminate various types of mismatch of supply and demand in the IT segment of the labor market.

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METHOD OF FORMING RECOMMENDATIONS USING TEMPORAL CONSTRAINTS IN A SITUATION OF CYCLIC COLD START OF THE RECOMMENDER SYSTEM

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Abstract

The problem of the formation of the recommended list of items in the situation of cyclic cold start of the recommendation system is considered. This problem occurs when building recommendations for occasional users. The interests of such consumers change significantly over time. These users are considered “cold” when accessing the recommendation system. A method for building recommendations in a cyclical cold start situation using temporal constraints is proposed. Temporal constraints are formed on the basis of the selection of repetitive pairs of actions for choosing the same objects at a given level of time granulation. Input data is represented by a set of user choice records. For each entry, a time stamp is indicated. The method includes the phases of the formation of temporal constraints, the addition of source data using these constraints, as well as the formation of recommendations using the collaborative filtering algorithm. The proposed method makes it possible, with the help of temporal constraints, to improve the accuracy of recommendations for “cold” users with periodic changes in their interests.

Keywords: recommendation system, temporal constraints, personalization of recommendations, area under the curve.

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1. Introduction

Recommendation systems are used to support consumer choice in the field of e-commerce, for example, in online stores, hotel booking systems, streaming video sales systems. Such systems are designed to predict a set of items that may be interesting to a specific user in the absence of information about the choice of specified items by this user. In making recommendations data on the choice of other users, as well as on the characteristics of selected items are used [1].

In the process of building such systems, a cold start problem usually arises due to the incompleteness of data on new users [2]. In the case of a new user or a new product, the latter are defined as “cold”. This means that information on these products is not enough to form accurate recommendations. The recommendation system can offer the necessary goods only after the user selects them on its own initiative. Such users are no longer “cold” and information about them can be used to support consumer choice. A cold start is an important problem in the recommendation system for occasional users who visit the corresponding site periodically, at long intervals, for example, to buy household appliances, books, and holiday travel [3]. Solving the problem of a cyclic cold start is associated with difficulties due to the lack of dependency information affecting consumer choice. Such implicit dependencies can be obtained based on the analysis of the sequence of user actions [4].

To solve the cold start problem, hybrid methods are used based on the complement of collaborative filtering by analyzing context data [5]. Also demographic data are used [6]. To account for cyclical changes in the interests of users, their temporal characteristics are used. Research in this direction uses two approaches: based on the user model and based on data filtering. In the first case, models for one and several users are used. In [7], a model of seasonal changes in the interests of the user was proposed, which is trained using gradient descent. The model of user preferences in the form of a temporal graph, which uses a random search when generating recommendations, is considered in [8]. The neural network model of multiple user behavior was proposed in [9]. In accordance with the second approach, using partial filtering of input data removes information that does not reflect the current interests of users. For filtering, a model based on a multilayer graph [10] is used, as well as the principles of self-learning [11] and active learning [12]. Approaches based on the model can more accurately describe the behavior of the user. Approaches based on input filtering are easily integrated with existing methods of building recommendations.

However, in general, the considered approaches are not focused on solving the problem of a cyclical cold start, since the latter is also characterized by a change in consumer interests and incomplete data on the choice of these consumers. To solve this problem, it is advisable to modify the input data based on the temporal model of the cycle of selection of known users, and then formulate recommendations for the new user. Therefore, the main idea of the research consists in combining the user behavior model, as well as modifying the input data when generating recommendations in a cyclical cold start situation.

2. Method of forming recommendations in situation of cyclic cold start using temporal constraints on input data

The developed method is intended for building recommendations in the case when input information, which is used to support the choice of the current consumer, is absent or irrelevant. Such information is usually absent for a new user and becomes irrelevant for irregular users when their interests change over time.

The method complements the input data set, which is used to build recommendations, before performing collaborative filtering. Supplement data is based on the use of temporal dependencies. Temporal dependencies have the form of weighted rules [13]. The weights of these rules are determined based on a random search [14]. Temporal dependencies in recommendation systems characterize selection sequences by well-known consumers of products that may be of interest to the current user. It is necessary to select and order the sequence of events (choice) for their formation, taking into account the context of this choice. A general approach to the selection of the initial subsets of events was proposed in [15].

The purpose of supplementing the input data is to set restrictions for the new, “cold” user in the form of permissible temporal dependencies of the choice of goods or services.

As a source of data in the recommendation systems, a matrix E of choice (for example, purchases) of the consumer is usually used. This matrix is sparse, that is, only a small part of the elements of the matrix is non-zero and displays the connection of users with items.

Each element e_{kj} of this matrix characterizes the choice of a consumer u_k from a set of consumers U of an item (product, service) i_j. Each non-zero element e_{kj} contains either the value of the product rating i_j or the number of units of this product purchased by the consumer u_k. For simplicity, let’s assume that the element e_{kj} contains the number of purchased items.

Traditionally, such a matrix summarizes information about each choice (purchase) e_{kj}^{n} of items i_j by the user u_k.

This selection is performed sequentially over a specified time interval $\left[\tau_1, \tau_N\right]$:

$$\forall e_{kj}^{\mathrm{n}} \, \exists \tau_n : \tau_1 \le \tau_n \le \tau_N, \tau_{n-1} < \tau_n. \quad (1)$$

This means that each element of the matrix E combines a set of consumer choices (purchases, ratings) ordered in time:

$$e_{kj} = \left\langle e_{kj}^{1}, e_{kj}^{2}, \ldots, e_{kj}^{n}, \ldots, e_{kj}^{\mathrm{N}} \right\rangle. \tag{2}$$

When several users select several $[\tau_1, \tau_N]$ products in an interval, let's obtain the sequence of selecting E_1^{N}:

$$E_1^{\mathrm{N}} = \left\langle e_{kj}^{1}, e_{lj}^{2}, \ldots, e_{km}^{n}, e_{lm}^{n+1}, \ldots \right\rangle. \tag{3}$$

This sequence contains a pattern of user behavior linking the purchase of goods i_j and i_m. Indeed, users u_k and u_l in the moments of time τ^1 and τ^2 chose the same product i_j. After some time, in moments τ^n and τ^{n+1} the same product i_m was also selected. Thus, the sequence (3) reflects the cyclical behavior of the users.

Such dependencies are not used in the traditional construction of recommendations, but are essential when cyclically cold start, since information about purchases periodically becomes irrelevant. As a result, when user preferences change, it is necessary to collect and analyze data on user needs.

An example of user selection cycles is shown in **Fig. 1**. This example shows the sequence of user selection in the six weeks preceding the appearance of a new user. At the moment of time τ_{11} a new, "cold" user u_6^{Cold} chooses an item i_3.

The selection sequence is shown in **Fig. 1** as follows. At the time point τ_1, the buyer u_1 chose the item i_1. At the time τ_2, the buyer u_4 chose the item i_4, etc.

Analysis of this sequence shows that the u_1 user's choice of a pair of items (i_1, i_4) is repeated twice in about 2 weeks and does not change when other interests of users change.

Therefore, it is advisable to consider this pair as a temporal limitation: after choosing i_1, a user has to choose i_4.

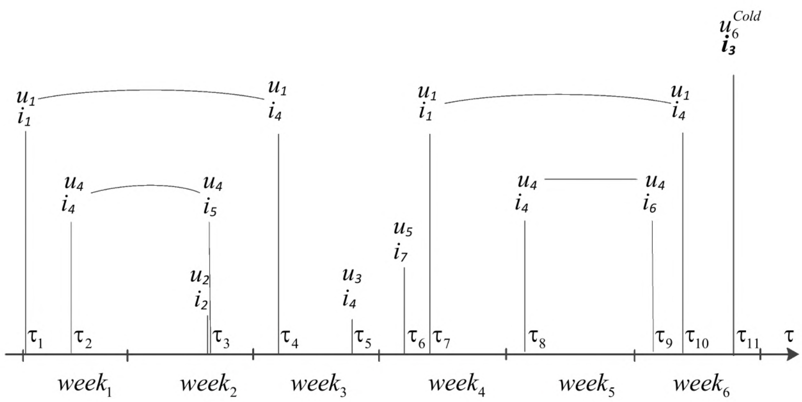

Fig. 1. The sequence of user selection

The buyer u_4, after selecting an item i_4 after about a week in one case, chose the product i_5, and in the other – i_6. Such dependencies should be considered as rules with the same weight, which corresponds to the probability of their realization.

Other buyers have chosen only one product; therefore there are no temporal dependencies for them.

Thus, there are 3 temporal dependencies in the given example: constraints (i_1, i_4) and rules (i_4, i_5) and (i_4, i_6).

These constraints and rules can be ad hoc or typical for a given domain, or for these items. If the frequency of occurrence of these constraints or rules in the input data exceeds a certain threshold value, then the dependencies between the specified objects should be considered typical. The threshold value depends on the domain. Therefore it should be chosen experimentally. Typical rules apply when specifying input to a new user.

In [13], several types of temporal rules are presented that are focused on decision-making support in process management. Such rules must be adapted to the given features of support recommendations. In this paper, we use a modified rule of the type "Next", which links two successive purchases at a given level of time granulation.

The temporal rule of a sequential selection of items in the recommendation system sets a pair of consecutive events for the selection of goods or services e_{kj} and e_{km} by the user u_k at times τ_n and τ_l at a given level of time granulation Δτ. This rule is set using the temporal operator X (Next) [13]:

$$\exists u_k : \left(e_{kj}, \tau_n\right) X \left(e_{km}, \tau_l\right) \big|\, | \tau_n - \tau_l | \approx \Delta\tau. \tag{4}$$

In accordance with rule (4), there are no intermediate purchases at the time level Δτ.

When selecting objects in the recommendation system sequentially temporal restriction sets a pair of consecutive events for which a strict order is set at a given level of time granulation Δτ:

$$\exists j, m : \forall k \left(e_{kj}, \tau_n\right) X \left(e_{km}, \tau_l\right) \big|\, | \tau_n - \tau_l | \approx \Delta\tau. \tag{5}$$

By virtue of the condition $\forall k,$ the constraint (5) will continue to be presented without the user's index k, as a pair $\left(e_j, e_m\right)$.

Restrictions (5) can be used to supplement information about a new user. Such dependences simulate a change in user interests and allow you to modify the source data in a cyclical cold start situation.

The formation and use of temporal limitations in building recommendations is carried out within the framework of the developed method. The method uses temporal dependencies for a given level of time granulation.

As input data are used: sales log containing a set of triples $L = \left\{\left(u_k, i_j, \tau_n\right)\right\}$; time interval for input data $\left[\tau_1, \tau_N\right]$; level of time granulation Δτ; threshold number α of repetitions of the rule. The last parameter is used when choosing temporal constraints.

The method includes the following steps.

Stage 1. Selection of a subset of sales log records for a given time interval $\left[\tau_1, \tau_N\right]$. This interval depends on the subject area. For example, for the task of booking hotels such an interval can be a year, sales of clothes – a season, and so on. The selection condition at this stage is $\tau_n \in \left[\tau_1, \tau_N\right]$.

Stage 2. Generalization of selection events for a given time granulation $\Delta\tau.$ At this stage, the values τ_n are summarized according to the level of detail – up to hours, days, etc.

Stage 3. Formation of pairs $\left(e_j, e_m\right)$ of sequential selection (purchases) of users at a given level of time granulation. The result of this stage is a set R that includes the pairs $\left(e_j, e_m\right)$ and the number of repetitions of these pairs n_{jm} on the set of input data:

$$R = \left\{\left(e_j, e_m, n_{jm}\right) : e_j X e_m, n_{jm} \geq 2\right\}. \tag{6}$$

Stage 4. Formation of temporal constraints C for the choice of users:

$$C = \left\{\left(e_j, e_m\right) : \forall j \left|\left\{e_j\right\}\right| = \left|\left\{e_j, e_m\right\}\right| = n_{jm}\right\}. \tag{7}$$

The restriction (7) means that after selecting an item $i_j,$ users must select an item i_m. The number of cases of choice is n_{jm}.

Stage 5. Selection of temporal restrictions for users.

At this stage, a subset of constraints is selected for each set C, for which $n_{jm} > \alpha$:

$$C_\alpha = \left\{\left(e_j, e_m\right) : n_{jm} > \alpha\right\}. \tag{8}$$

The result of this phase is a set of constraints for all users.

Stage 6. Supplementing the input data L with constraint records according to (8) for new, "cold" users.

The resulting log L^{Cold} has the following form:

$$L^{Cold} = L \cup \left\{ \left(u_k^{Cold}, i_m, \tau_l \right) : n_{jm} > \alpha \right\}. \quad (9)$$

Stage 7. Building recommendations using traditional methods, in particular collaborative filtering [16]. The result of this stage is a list of recommended items for a new user. The list takes into account cycles of changes in the interests of known users.

3. Experimental results

Consider the implementation of the method on the example of the sequence of user selection, shown in **Fig. 1**. The sales lot L is presented in this figure in a graphical form. The level of time granulation $\Delta\tau$ is one week. The base time interval $[\tau_1, \tau_{10}]$ covers all 6 weeks. The threshold number of repetitions α is 1. The original data are supplemented for the new user u_6^{Cold}.

The phased implementation of the method is presented in **Table 1**.

Table 1

The results of the method in stages

Stage number	Stage results	Comments
1	L	The interval $[\tau_1, \tau_{10}]$ covers all input data. Therefore, the log$L$ is transferred to the second stage in full
2	$\tau_1, \tau_2 \in week_1, \; \tau_3 \in week_2,$ $\tau_4, \tau_5 \in week_3,$ $\tau_6, \tau_7 \in week_4,$ $\tau_8 \in week_5,$ $\tau_9, \tau_{10} \in week_6$	The input data instead of the exact time stamps τ_1–τ_{10} get values with a detail of up to one week
3	$R = \left\{ \begin{matrix} (e_1, e_4, 2), (e_4, e_5, 1), \\ (e_4, e_6, 1) \end{matrix} \right\}$	A set of temporal dependencies are formed for all known users
4	$C = \{(e_1, e_4)\}$	A set of constraints C is formed from a single repeating element
5	(e_1, e_4)	The constraint satisfies the condition $n_{14}>\alpha$
6	$L \cup (u_1, i_4, \tau_{11})$	The input data of the new user u_6^{Cold} is supplemented with the constraints

The restriction obtained in step 5 makes it possible to establish a potential connection between the choice of the user u_6^{Cold} and the known preferences of other users. This connection is depicted by the horizontal arrow in the oval in **Fig. 2.**

In **Fig. 2** input data are presented in the traditional form, without taking into account time stamps. Information about the new user u_6^{Cold} includes the selection of item i_1. This choice does not allow comparing its interests with the choice of other users. The addition of data element e_{64} allows to establish communication with the user u_1. This connection is reflected by vertical arrows. Adding a new link gives the opportunity to form recommendations using collaborative filtering.

Experimental verification of the method was performed using the Online Retail dataset located in the UCI storage.

This kit is a sales log for a UK chain of gift shops. This network makes wholesale purchases. Such purchases are repeated at regular intervals. Interest in gifts may also change cyclically. As part of the experiment, a subset of 10.4 thousand records was selected that contain repeated purchases by the same users, which allows them to find temporal constraints. A subset of the data was supplemented by a record of one purchase of a new buyer.

During the experiment, the value of AUC (Area Under the Curve) was compared for the recommended list of the most popular items, as well as the recommendations obtained using temporal constraints. In the first case, for the dataset used, the AUC value was 0.71, and in the second – 0.72. The increase in accuracy is small, but it should be borne in mind that a small dataset was used. In general, the experimental results indicate the influence of temporal limitations. To further improve the accuracy, it is necessary to use weighted temporal dependencies that define possible patterns of user choice.

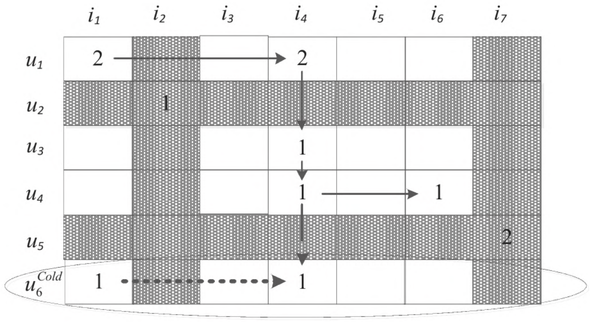

Fig. 2. Updated raw data

4. The discussion of the results

The result of the work is the method of forming recommendations in the situation of a cyclical cold start. This situation occurs for users who occasionally turn to the recommendation system.

The recommended list of items that are obtained as a result of the completion of the method allows personalizing the consumer choice in the conditions of incomplete data about the user of the recommendation system.

The difference of the proposed method lies in the preliminary modification of the input data of the new user, taking into account the temporal restrictions on the choice of existing consumers.

The advantage of the method is that it is possible using temporal constraints to clarify recommendations for users who access the recommendation system occasionally, at long intervals. Temporal limitations make it possible to form a connection between the choice of new and well-known users.

The disadvantage of the method is that the temporal limitations used when forming recommendations and, as a result, the composition of the recommended list of items, largely depend on the time interval in which the initial data is selected.

The method has limitations related to the features of offline and online modes of operation of the recommendation system. The method is focused only on the online mode of operation, since it does not take into account the entire data set, as in offline mode, but only the most relevant input data, reflecting the cycle of changing user priorities.

The developed method is intended for use in the situation of a cyclic cold start of the recommendation system associated with the periodic change in user preferences. The method complements the existing approaches to building recommendations based on collaborative filtering.

5. Conclusions

The problem of building a list of recommended objects in the situation of a cyclic cold start characterized by a periodic change in consumer preferences is considered. This complicates the construction of recommendations for new, "cold" users. In such a situation it is necessary to consider patterns that characterize changes in consumer interests. These patterns set constraints when forming recommendations and are usually not taken into account within the framework of existing approaches.

A method for constructing recommendations under cyclic cold start conditions using temporal constraints is proposed. The method includes the steps of forming temporal constraints, supplementing data for new users based on these constraints, as well as generating recommendations using an augmented data set.

This method, in contrast to existing ones, allows using cyclical changes in the choice of consumers to personalize recommendations to new users.

The proposed method makes it possible to increase the efficiency of forming recommendations for new "cold" users in a situation of periodic changes in their interests, taking into account temporal limitations for known users.

With further improvement of the method, it is also assumed to take into account the weighted temporal dependencies that characterize typical patterns of user choice over time. The key difference between the considered restrictions and such dependencies is that the latter do not set mandatory, but possible options for changing user preferences.

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HIERARCHICAL CLUSTERING OF SEISMIC ACTIVITY LOCAL TERRITORIES GLOBE

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Abstract

In article, the interrelation between energy parameters of Globe moving in a system Sun-Earth-Moon has been established. It includes features of a seasonal energy condition of an internal core of Earth and the key energy parameters of tectonic activity of seismically dangerous local territories of the planet. These parameters have been systematized by means of a clustering method hierarchical. The mechanism of energy influence of core Earth fluctuations on variations of axial rotation speed of the Globe and level of seismic activity has been grounded. The phenomenon of a periodic oscillation of planet condition seismic and effect of asymmetric distribution of the emergency situations (ES) of tectonic origin on the Earth's surface has been established. For the first time, ranging of the seismically fissile local territories of the Globe in the parameters determining the level of seismic activity and ranges of magnitudes was carried out. Based on these results the effect of division of the seismically fissile local territories into three main clusters that characterized by rather high, average and low degrees of seismic activity was established. Join of the ranged seismically fissile local territories of the Globe permit to establish zones with various degree of seismic activity along the section of various geophysical plates.

The results received in article are a basis for further carrying out complex assessment of interrelations between key parameters of moving Globe in a system Sun-Earth-Moon and key parameters of tectonic danger of the seismically fissile local territories of Earth. It is base for further increase in effectiveness of monitoring of origin tectonic emergency by development of neural network prognostic models.

Keywords: emergency situation, seismic activity, seismic danger, monitoring of emergency situations, cluster analysis.

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1. Introduction

Many processes occurring during the operation of the natural-artificial-social system of the Earth and their mutual transformation gives rise to many natural phenomena dangerous to the Earth's biosphere, such as earthquakes, tsunamis, volcanic eruptions, floods, hurricanes and others [1, 2].

The tendency to an abrupt increase in the number and destructive power of natural disasters over the past few decades of the life of society leads to a deterioration of socio-economic and environmental consequences. It indicates the need to develop effective measures to prevent and eliminate emergencies of various nature on the globe [3–5].

A promising direction for solving this problem is the development of an effective hazard detection system at the stage of their inception. Also, the causes will be establishing of the occurrence these factors manifestations and effects on them in order to prevent the occurrence of emergencies. This has been implemented on the basis of the classical control loop presented in **Fig. 1** [6–9].

This article is part of a planned set of scientific studies aimed at developing a safety system. This eliminates or minimizes losses as much as possible under conditions of manifestation of an emergency. The work is focused on studying the processes of emergence and spreading of emergencies of lithospheric origin, which represent or may pose a serious danger to the life of society [10, 11]. A general assessment of the degree of negative impact of emergency situations of lithospheric origin on the conditions for the normal functioning of the natural-technogenic-social system is carried out using tectonic parameters characterizing the level of seismic danger of local Earth territories. A comprehensive assessment of the unsTable seismically the parameters area was carried out using a set of basic multidimensional statistical methods. In this paper the solution of the problem was implemented using cluster analysis.

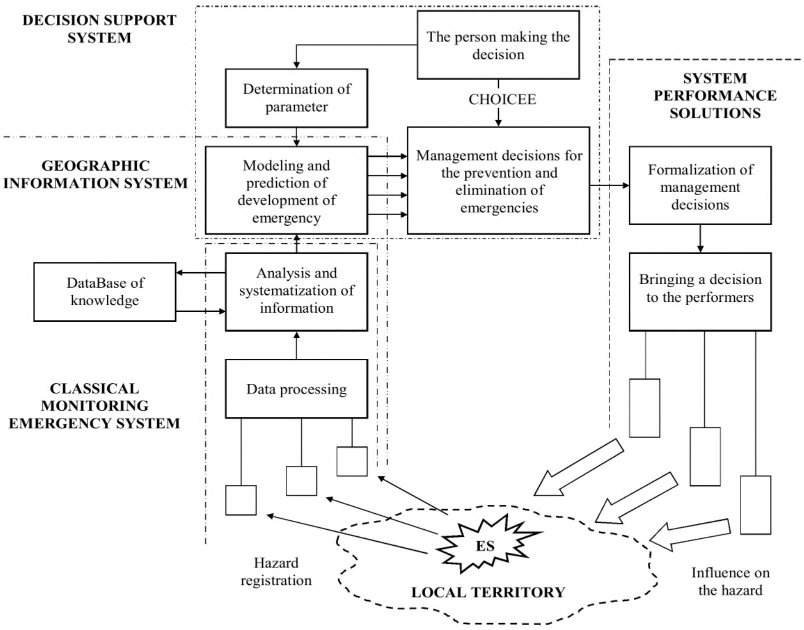

Fig. 1. Diagram of the emergencies monitoring structure as a means of control [15]

2. Methods of research the clustering of seismic activity local territories globe

2. 1. Analysis of recent achievements and publications

The dynamics of the physical processes of the Sun-Earth-Moon system affecting the seismic hazard level of the local territory functioning can be schematically represented according to **Fig. 2–4**. This can be characterized by the following spatial constructions within the solar galaxy.

1. The axis of rotation of the Earth in the celestial sphere describes a complex wave-like trajectory. The points of the axis of rotation are at an angular distance of about from the pole ecliptic (**Fig. 2**). The vertex of the cone coincides with the Earth center. The points of equinoxes and solstices move along the ecliptic towards the sun. Moments of gravitational forces influence on

the equatorial bulges and vary depending on the positions of the Moon and the Sun relative to the Earth. When the Moon and the Sun are in the plane of the Earth's equator the moments of forces disappear. If tilts of Moon and Sun are the maximum, then the magnitude of the torque will be greatest. The nutations, owing to fluctuations in the moments of the forces of the axis of rotation of the Earth have been observed by consist of a series of small periodic oscillations. The main nutations have a period of 18.6 years – the time of the orbital nodes of the Moon. Movement with this period occurs on an ellipse. The major axis of the ellipse is perpendicular to the direction of the precessional motion and is equal to; small – parallel to it and equal. Next in magnitude of the amplitude are the components with a period of 0.5 year, 13.7 days, 9.3 years, 1 year, 27.6 days etc., therefore the trajectory has the form of "thin laces" (shown on the enlarged fragment in the left part of **Fig. 2**) [12–19].

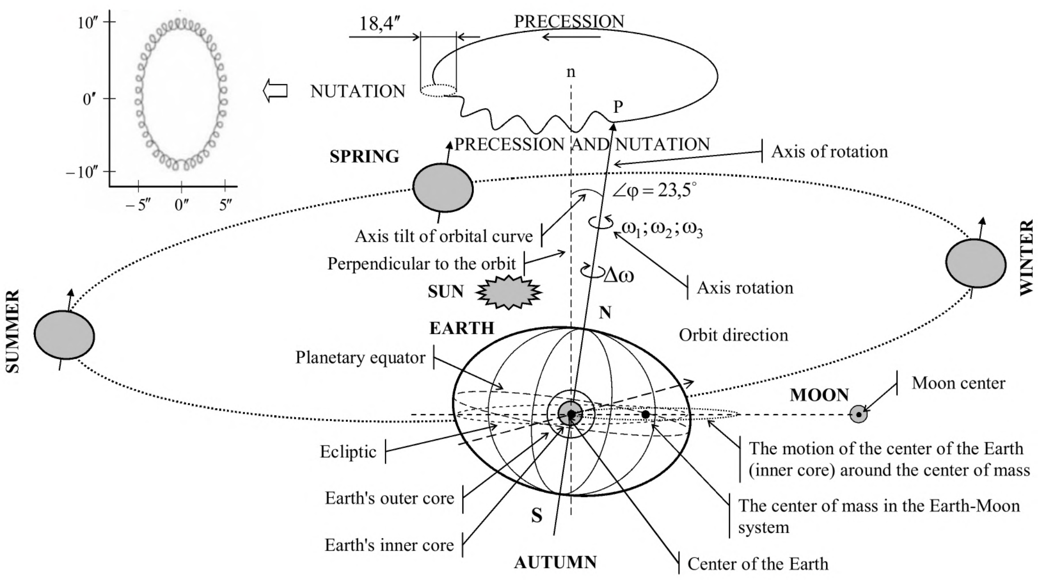

Fig. 2 Motion diagram of the inner core of the Earth in the Sun-Earth-Moon system

2. The pressure from the solid inner core and the surrounding melt (outer core) onto the mantle arises as a result of the eccentric revolution of the Earth's shell around the displaced inner core, which squeezes the shell from the inside. The forces compressing the shell of the sphere (planet) and drawing it inward to the core arise in other parts of the planet. This process has two components: impact at the expense of the annual displacement of the center nucleus relative to the center of the globe (**Fig. 2–4**); impact at the expense of eccentric circulation of the core relative to the lower mantle, when due to the difference in angular rotation velocity of the core and lower mantle (ω_1 – angular velocity of rotation of the mantle; ω_2 – angular velocity of rotation of the outer core; ω_3 – angular velocity of rotation of the inner core; $\Delta\omega = \omega_2 - \omega_1$ – angular velocity of rotation of the outer core relative to mantle ("western drift")), therefore, there are zones of high pressure and vacuum ($P_1 \neq P_2$, where P_1 and P_2 are indicators of pressure of the inner core of the globe on its surface), affecting the level of seismic activity of the surface of the Earth (**Fig. 3**). As long as there is a difference in the angular velocity of rotation and displacement of the nucleus, the appearance of such zones will be maintained [20–25].

3. Internal elastic stresses arise in the process of moving lithospheric plates (**Fig. 4**), which are energy sources of earthquakes [26–30]. The occurrence depth of elastic stresses depends on the nature of a movement plates. The relative motion of lithospheric plates leads to the emergence of shallow (not deeper than 20–25 km) earthquake sources and dipping of lithospheric plates into the mantle initiates the appearance of sources of deep (exceeding 70 km) earthquakes. The probability of elastic stresses – sources of earthquakes decreases with increasing distance from the interface of the lithospheric separation plates.

4. Surface and bulk seismic waves are the propagation factors of earthquake hazards Z_0, that can cause secondary earthquakes [30, 31].

5. The probability of mutual amplification or weakening of bulk seismic waves increases in the process of spatial-vibrational movement of the Earth's internal core and its effect on the external core. Consequently, the possibility of secondary earthquakes Z' increases also [32].

6. The possibility of the impact of surface and bulk seismic waves on stresses in the lithosphere is not excluded. It occurs near earthquakes and initiates the occurrence of a seismic hazard Z'' propagation chain reaction [33–35].

7. The territorial-temporal changes in the intensity of the natural electromagnetic field pulses of the Earth initiating anomalous processes in the atmosphere occur due to the movement of the Earth's inner core has been established [36–42].

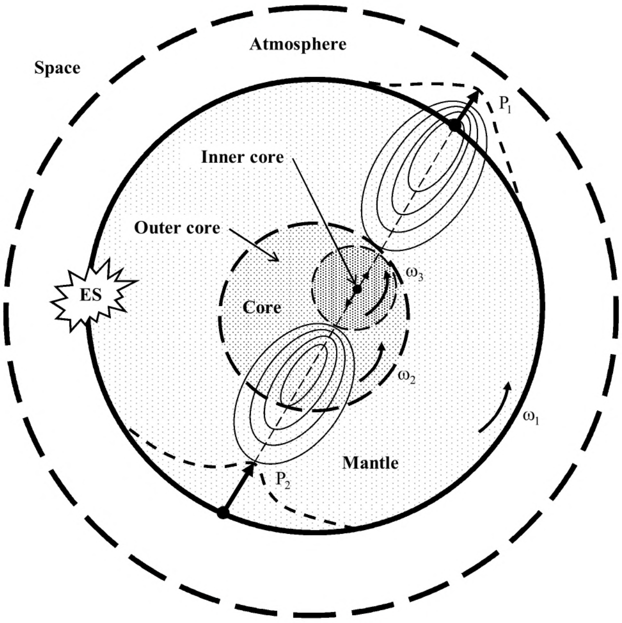

Fig. 3. Influence diagram of internal core oscillations on seismic activity

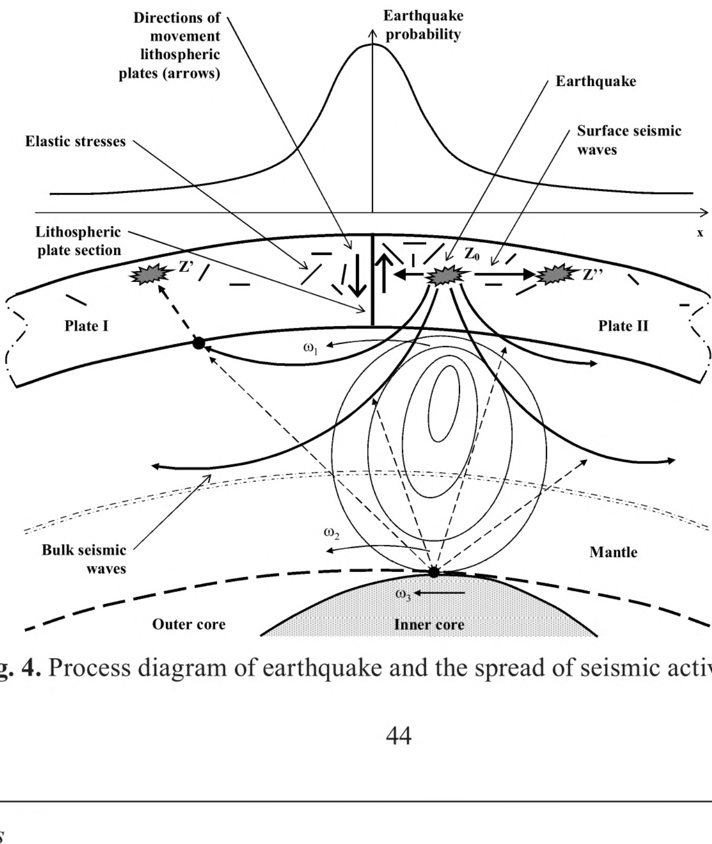

Fig. 4. Process diagram of earthquake and the spread of seismic activity

Thus, combining the analysis results of the impact dynamics and energy of the internal physicochemical processes of the Earth on the origin generating tectonic processes allowed to formulate an approach to studying the nature of seismic phenomena. It is an important tool for analyzing the results of civil defense research on the development of models for the development of ES tectonic nature.

2. 2. Problem statement and solution

The development of scientific and technical foundations creating an artificial intelligence system for monitoring emergencies of tectonic origin was the article purpose. The development of the scientific and technical foundations of system ascertains two necessary requirements:

1) increasing the efficiency of processing information about the processes occurring in the Sun-Earth-Moon system (the processes are schematically presented in **Fig. 2–4**);

2) conducting scientific research is aiming at the classification and ranking of multidimensional statistical methods of local areas of the globe in seismic activity terms. Cluster analysis of data using statistical packages STATISTICA 6.1 and SPSS 20 has been performed in this article.

The purpose of cluster analysis is to find groups of similar objects in the data sample, the so-called clusters characterized by the following main properties: density, dispersion, size, shape and separability, according to [43, 44]. By density is meant a property that defines a cluster as an accumulation of points in data area. It is relatively dense compared to other regions of area that contain either a small number of points or do not contain them at all. Dispersion characterizes the degree of dispersion points in area relative to the cluster center. Cluster size is closely related to variance. The shape of the cluster is determined by the position of the points in area. The definition of "connectedness" of points in a cluster as a relative measure of the distance between them is required when depicting clusters of various shapes. Distance measures are usually not limited from above and depend on the choice of index (scale) measurements. Separability characterizes the degree of cluster overlap and how far apart these located in area.

The Euclidean distance when determining a measure of distance is one of the most known

$$d_{ij} = \sqrt{\sum_{z=1}^{p} \left(X_{iz} - X_{jz}\right)^2}, \quad (1)$$

where d_{ij} – distance between objects *i* and *j*; X_{iz} – absolute a values *z*-th variable for *i*-th objects; X_{jz} – absolute a value *z*-th variable for *j*-th objects.

However, the similarity score strongly depends on differences in data shifts when analyzing the distance measure. Thus, variables characterized by large absolute values and standard deviations can suppress the influence of variables, which is characterized by small absolute values and standard deviations. To reduce this effect, the process of data standardization in the article has been carried out before determining the distance measure. It is based on the normalization of variables to unit variance and zero mean:

$$X_{iz}^{*} = \frac{X_{iz} - M\left[X_i\right]}{\sigma_{X_i}}; \; X_{jz}^{*} = \frac{X_{iz} - M\left[X_j\right]}{\sigma_{X_j}}, \quad (2)$$

where X_{iz}^{*}, X_{jz}^{*} – standardized values *z*-s variables for *i*-th and *j*-th objects; $M\left[X_i\right]$, $M\left[X_j\right]$ – mathematical expectations for variables *i*-th and *j*-th objects; σ_{X_i}, σ_{X_j} – standard deviations, characteristic of variables *i*-th and *j*-th objects.

Known cluster analysis methods can be divided into two groups-hierarchical and non-hierarchical methods.

The essence of hierarchical clustering is to successively merge smaller clusters into larger, so-called agglomerative methods, or to divide large clusters into smaller, so-called divisional methods.

In this article, the Ward method has been used to carry out hierarchical clustering of the Earth's territory in terms of seismic activity. This method is one of the widely used agglomerative methods. The advantage of the Ward method is the use of analysis of variance to estimate the distance between the clusters. This is different from all other agglomerative methods. The method minimizes the sum of dispersion squares for clusters that can be formed at each step. New results have been obtained using the Ward method.

In this paper, the system of dividing maps into detached sheets for cluster analysis of the territory of the globe on the level of seismic activity has been used. It is based on the international plots of 1:1,000,000 scale maps in accordance with **Fig. 5**. At the same time, the division into rows by parallels is made from the equator at every 4^{o} latitude. Rows represent letters of the Latin alphabet: A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, V, W. The columns in their borders coincide with 6^{o} the Gauss-Kruger projection zones. The columns are numbered from the meridian $\pm 180^{o}$ to the east and denoted (by number) by Arabic numerals [45].

The article measures the Euclidean distances between the standardized values of the variables that determine the degree of seismic activity of seismically active local territories of the Earth (obtained by dividing the maps into separate sheets of 1:1,000,000 scale) over the period 2009–2018 have been determined. The initial sample included 4580 observations of the occurrence of earthquakes with a magnitude $M \geq 4$ on the Richter scale over 2640 local territories of the globe. The following indicators have been used for cluster analysis of local Earth territories by seismic activity: K – the number of earthquakes; M_{max} – the maximum magnitude of earthquakes arising; M_{min} – the minimum magnitude of earthquakes. A fragment of the calculations results have been presented in **Table 1**.

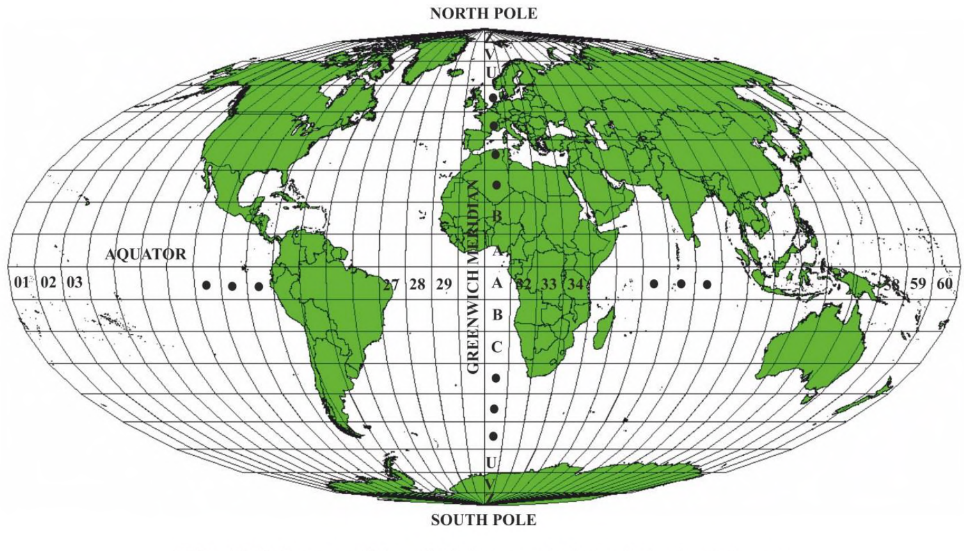

Fig. 5. Scheme of the division cards into detached sheets

The process of using the step-by-step agglomerative method for combining seismically active (in terms of indicators K, M_{max} and M_{min}) local territories of the Earth as a result of dividing maps into detached sheets of a 1:1,000,000 scale into clusters according to the degree of seismic activity has been presented in **Fig. 6**.

The result of hierarchical clustering by the Ward method according to the degree of seismic activity (earthquakes with magnitude $M \geq 4$ on the Richter scale have been taken into account) for the period 2009–2018 local territories of the Earth obtained as a result of dividing maps into detached sheets of a scale 1:1,000,000 have been presented in **Fig. 7**. It can be noted that a comprehensive analysis of the local territories of the globe according to the degree of seismic activity allowed to rank the seismically active territory of the planet into three main clusters at a distance of 100 Euclidean distances.

Table 1

A fragment of the calculations results of the Euclidean distances between the standardized values of the variables determining the degree of seismic activity of seismically active local territories of the Earth

	N-A-15	N-A-16	N-A-17	N-A-18	×	S-Q-1	S-Q-55	S-Q-56	S-T-6
N-A-15	0,0	0,4	2,3	1,7	×	0,3	1,2	1,7	0,6
N-A-16	0,4	0,0	2,7	2,1	×	0,2	1,2	1,8	0,5
N-A-17	2,3	2,7	0,0	0,6	×	2,6	2,4	2,5	2,5
N-A-18	1,7	2,1	0,6	0,0	×	2,0	1,9	2,0	1,9
×	×	×	×	×	×	×	×	×	×
S-Q-1	0,3	0,2	2,6	2,0	×	0,0	1,3	1,8	0,6
S-Q-55	1,2	1,2	2,4	1,9	×	1,3	0,0	0,5	0,7
S-Q-56	1,7	1,8	2,5	2,0	×	1,8	0,5	0,0	1,2
S-T-6	0,6	0,5	2,5	1,9	×	0,6	0,7	1,2	0,0

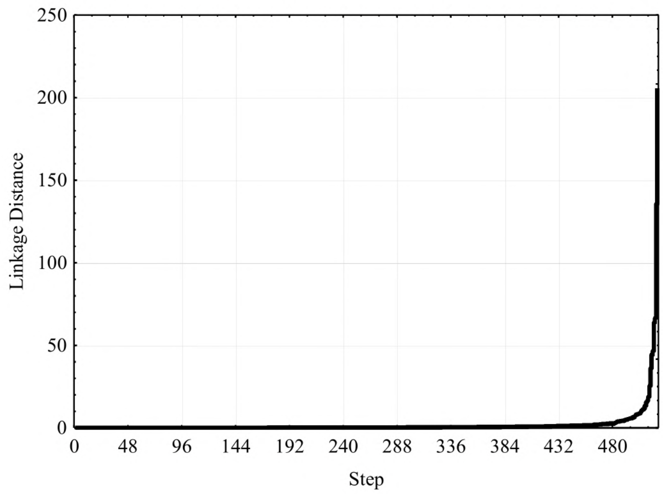

Fig. 6. Schedule of step-by-step merging of seismically active local territories of the Earth obtained as a result of dividing maps into separate sheets of 1:1,000,000 scale into clusters according to the degree of seismic activity for the period 2009–2018

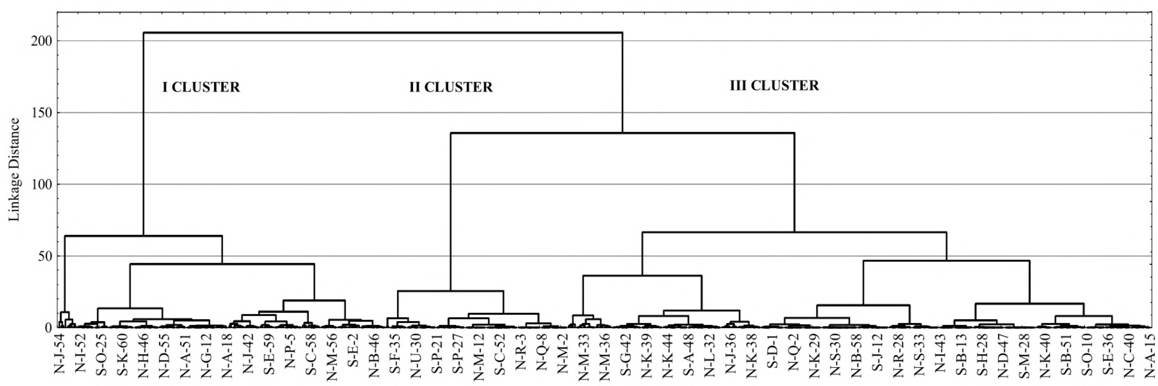

Fig. 7. Dendrogram of clustering of seismically active local Earth territories obtained as a result of dividing maps into detached sheets of 1:1,000,000 scale according to the degree of seismic activity over the period 2009–2018 (on the dendrogram there are numbers of cards in 10 units increments)

The first cluster, with a high degree of seismic activity over the period 2009–2018 includes the following seismically active local territories of the Earth. It has been obtained as a result of dividing the maps into detached sheets of 1:1,000,000 scale, namely: N-A-17; S-L-18; N-D-46; N-J-55; S-E-18; N-B-46; S-E-60; N-E-55; N-N-59; N-N-9; N-C-52; N-N-60; N-A-46; N-A-47; S-F-19; S-E-2; N-D-15; S-I-19; N-E-14; S-E-58; N-H-45; S-A-53; S-A-50; N-D-16; N-L-56; N-M-56; S-K-59; N-G-41; N-G-54; N-N-2; N-J-43; N-A-52; S-C-57; S-A-47; S-D-58; S-C-58; S-J-18; N-G-51; S-B-54; S-H-1; N-B-17; N-H-54; N-N-3; N-R-6; N-F-51; N-P-5; N-K-33; N-K-43; N-B-51; N-I-53; N-N-57; S-H-19; S-I-1; N-C-51; S-B-52; S-E-59; S-C-50; S-O-26; N-L-55; S-B-48; N-G-52; N-J-38; N-O-58; S-B-55; S-G-1; N-J-42; N-O-6; N-H-40; N-I-54; N-I-35; N-J-35; N-H-52; N-N-1; N-K-34; N-K-35; N-A-18; N-D-54; N-C-20; S-B-18; N-O-57; S-M-58; N-C-17; S-P-26; S-A-55; N-E-13; N-G-12; S-D-18; N-F-47; N-J-44; S-N-32; N-H-12; S-H-18; N-N-46; S-F-20; S-O-35; N-A-51; S-B-53; N-G-46; N-M-57; S-C-51; N-B-52; S-A-54; S-A-51; S-A-52; S-D-2; N-D-55; S-J-60; S-I-18; N-B-47; N-C-54; N-I-11; N-C-19; S-E-19; S-A-56; N-E-19; N-H-46; N-L-45; S-B-50; S-A-27; S-O-55; N-H-48; N-K-10; N-K-55; N-M-9; S-A-28; S-K-60; N-O-4; N-N-25; S-I-12; N-N-58; N-N-56; S-I-60; N-C-45; S-L-58; S-F-58; S-O-25; N-C-46; N-H-41; S-P-23; N-E-16; N-E-18; N-R-54; S-A-18; N-F-46; N-I-46; N-I-52; S-C-48; N-I-38; S-E-1; N-K-54; S-B-56; S-F-59; N-L-35; N-J-34; S-F-1; N-J-54.

The second cluster, with a middle degree of seismic activity over the period 2009–2018, includes the following seismically active local territories of the Earth obtained by dividing maps into detached sheets of 1:1,000,000 scale, namely: N-A-36; N-F-24; N-M-2; N-Q-55; S-C-55; S-F-55; S-G-43; S-G-56; N-G-37; N-J-29; N-L-10; N-N-48; N-Q-8; N-B-10; N-D-19; N-G-19; N-G-49; S-A-29; S-O-29; S-T-6; N-H-32; N-M-45; N-R-3; N-U-31; N-B-56; N-P-7; S-P-20; N-J-47; N-N-51; N-N-54; N-T-18; S-C-47; S-C-52; S-G-11; S-H-11; S-I-14; S-J-14; S-J-54; S-Q-55; N-H-35; N-J-17; N-J-26; N-M-12; S-M-52; S-O-57; N-M-54; N-S-15; S-F-49; S-J-19; N-C-55; N-P-8; S-C-36; S-P-27; N-H-11; N-K-42; S-G-44; S-G-52; S-L-36; N-D-21; N-O-8; S-G-20; S-H-20; S-P-21; N-A-50; N-N-8; S-N-57; N-B-55; N-O-7; S-O-27; S-P-28; S-Q-56; N-C-23; N-U-30; S-C-46; S-L-46; S-M-54; S-P-35; N-C-13; S-C-19; N-N-47; S-N-21; N-F-12; S-F-35; S-N-31; S-O-28; N-E-17; S-B-46.

The third cluster, with a low degree of seismic activity over the period 2009–2018, includes the following seismically active local territories of the Earth obtained as a result of dividing the maps into detached sheets of 1: 1,000,000 scale, namely: N-A-15; S-J-39; S-M-51; N-J-45; S-H-41; S-C-56; S-N-8; S-O-9; S-K-28; S-Q-1; N-C-40; N-J-52; S-L-47; N-E-15; S-K-45; N-Q-5; S-H-43; N-J-31; N-L-18; S-C-37; S-E-36; S-H-12; N-B-18; N-H-47; S-K-38; S-P-24; N-C-18; S-B-28; N-J-14; N-D-37; S-O-10; N-B-50; S-I-28; S-J-28; N-P-1; N-J-46; S-O-19; S-D-19; N-D-50; N-I-48; S-B-51; N-J-30; S-A-17; S-B-17; N-E-20; N-L-9; S-P-56; N-D-22; N-F-18; S-N-6; N-K-40; S-L-59; N-F-50; S-F-36; S-A-35; N-A-16; N-C-21; N-H-24; N-H-36; S-J-55; S-M-28; S-P-58; N-O-53; N-R-4; S-A-15; S-E-56; S-F-26; S-G-35; S-G-59; S-I-11; N-D-47; N-F-17; N-I-12; N-K-28; S-K-18; S-N-30; S-O-34; N-L-25; N-P-57; N-T-30; S-H-28; S-C-17; S-L-17; S-J-13; S-O-20; N-B-24; N-K-48; N-N-45; S-A-13; S-B-13; S-B-29; S-I-51; S-M-47; N-D-20; N-L-43; N-L-48; N-Q-1; S-I-31; S-N-35; N-I-43; N-A-25; N-H-22; N-N-30; N-O-54; N-O-55; S-D-42; N-O-3; N-Q-31; N-S-33; N-V-30; N-V-36; S-B-36; N-D-40; N-M-26; N-E-4; N-L-53; N-O-40; N-Q-22; N-R-28; N-F-5; N-L-46; N-M-44; S-F-33; N-B-25; N-F-19; N-M-37; S-C-42; S-D-37; S-J-12; S-J-44; N-E-23; S-E-20; N-I-32; S-C-18; S-J-38; S-P-57; S-F-42; S-K-44; N-B-58; N-E-12; N-F-55; N-O-56; S-K-1; S-L-37; S-P-55; N-P-10; N-P-6; N-Q-3; N-S-30; S-B-5; S-C-12; S-F-9; S-I-50; S-G-28; N-B-40; N-G-45; N-J-32; N-K-29; S-L-13; N-P-60; N-Q-6; N-U-51; S-A-26; N-C-24; N-L-26; N-O-36; N-O-51; N-Q-2; N-V-45; S-B-42; S-C-28; S-A-42; N-D-23; S-D-59; S-G-12; S-D-28; N-E-47; S-D-1; N-G-23; N-K-26; N-P-25; N-J-25; N-G-42; N-A-26; N-J-37; N-G-40; N-L-44; N-K-38; N-S-29; N-C-16; N-J-53; N-K-9; S-B-47; S-F-2; N-H-39; S-G-60; S-D-38; N-J-36; N-M-32; N-J-40; N-K-37; N-O-5; N-D-17; N-J-41; N-Z-40; S-C-35; N-G-48; N-L-32; S-C-49; S-G-19; N-G-39; S-N-34; N-G-47; N-P-58; N-K-45; S-A-36; N-H-53; S-A-48; N-D-51; N-E-51; N-E-46; S-I-40; N-F-54; N-E-5; N-J-10; S-E-42; N-F-23; N-K-44; N-M-55; N-S-31; N-D-39; N-I-40; N-Q-28; N-K-53; N-N-4; N-O-25; N-H-42; N-K-39; N-I-36; N-N-40; N-E-37; S-H-60; N-V-29; S-B-49; N-I-44; N-I-45; N-H-44; S-G-42; N-I-47; N-T-32; N-I-42; N-L-51; N-L-54; N-O-49; N-I-34; N-L-37; N-L-33; N-M-36; N-I-39; N-N-33; N-K-36; N-L-34; N-J-33; S-F-60; N-M-1; N-J-39; N-L-36; N-M-33; N-L-38; N-O-33; N-U-11; N-M-34; N-M-35; N-N-35; N-N-34.

3. Discussion of the research results to the clustering of seismic activity local territories globe

The remainders of the local Earth territories obtained as a result of dividing maps into detached sheets of a scale of 1:1,000,000 were not seismically active for the period 2009–2018. The results of the clustering of the local territories of the Earth obtained as a result of dividing the maps into detached sheets of a scale of 1:1,000,000 according to the degree of seismic activity for the period 2009–2018 graphically for the northern hemisphere have been presented in **Fig. 8** (for the southern hemisphere in **Fig. 9**). The summarized results have been presented in **Fig. 10**.

Areas of research were for time period specified:

1) the arisen earthquakes magnitude on the Richter scale;

2) 2640 local territories of the Globe received as result of division cards into single sheets of scale 1:1000000.

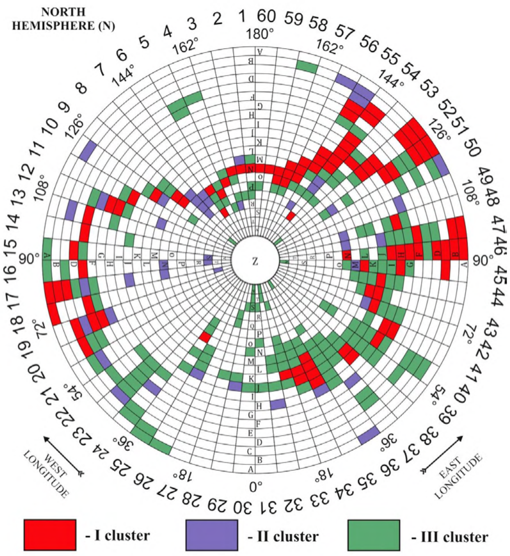

Fig. 8. Cartographic presentation of clustering results seismically active local territories of the northern hemisphere of the Earth obtained as a result of dividing maps into separate sheets of 1:1,000,000 scale according to the degree of seismic activity for the period 2009–2018

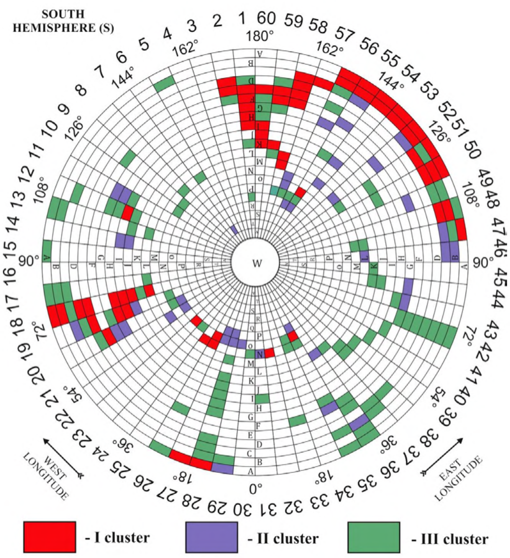

Fig. 9. Cartographic presentation of clustering results seismically active local territories of the southern hemisphere of the Earth obtained as a result of dividing maps into detached sheets of 1:1,000,000 scale according to the degree of seismic activity for the period 2009–2018

From the data analysis **Fig. 8–10** that:

1) territory of the Earth is divided into areas with different levels of seismic activity, which corresponds to different degrees of risk emergency situations of tectonic origin;

2) seismically active local areas have been concentrated along the section of lithospheric plates;

3) occurrence of earthquakes in seismically active local territories has been synchronized with the kinetics and energetics of the motion of the Earth in the Sun–Earth–Moon system.

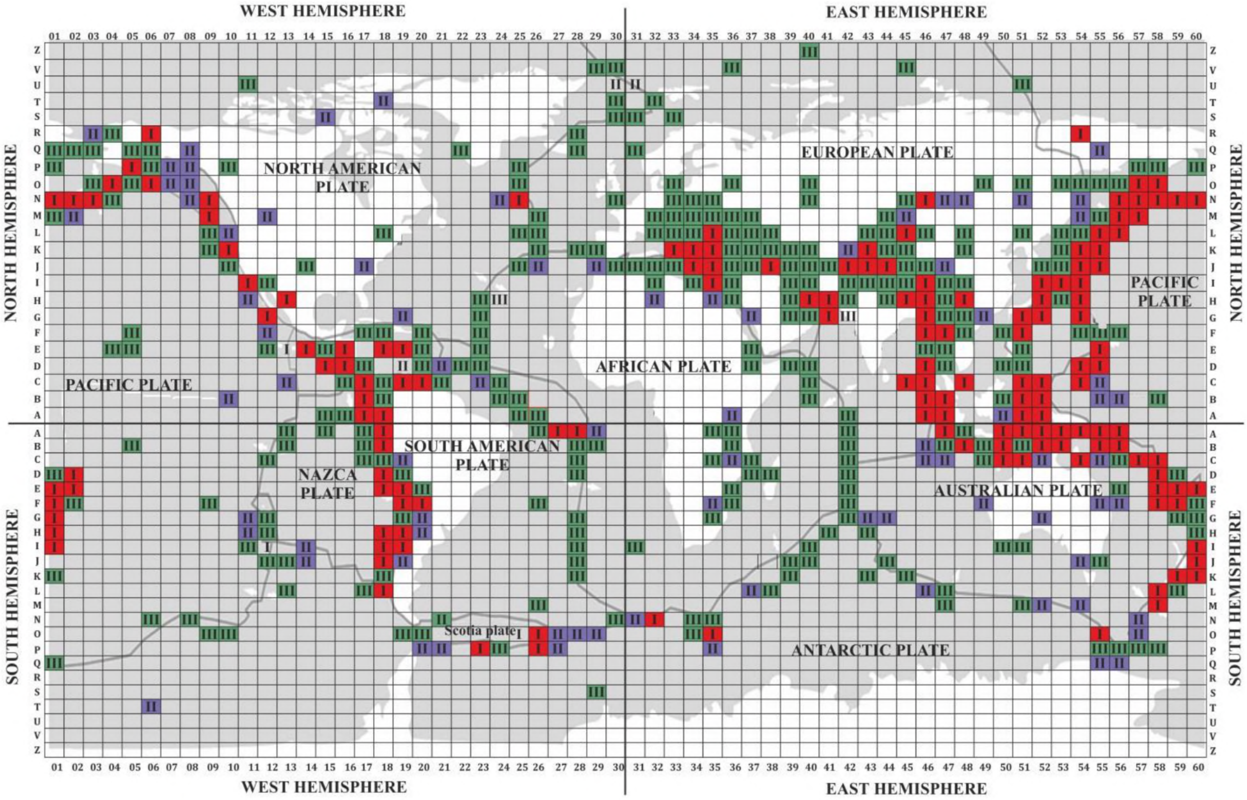

Fig. 10. A cartographic representation of the results clustering seismically active local areas of the globe obtained as a result of dividing maps into detached sheets of a scale of 1:1,000,000, according to the degree of seismic activity over the period 2009–2018

The results of the clustering of the planet's territory in terms of seismic activity over the period 2009–2018 allowed to single out the following zones with a relatively high degree of seismic activity. These zones unite local territories of the Earth obtained as a result of dividing maps into detached sheets of 1:1,000,000 scale constitute the first cluster.

Zones with a relatively high degree of seismic activity are:

– in the northern hemisphere:
  – along the section of the European and Pacific plates;
  – around the Philippine Plate;
  – along the section of the North American and Pacific plates;
  – around the Caribbean plate;
– in the southern hemisphere:
  – along the section of the Australian and Pacific plates;
  – along the section of the South American plate and the Nazca plate.

Zones with a relatively low seismic activity obtained in this way are:

– in the northern hemisphere:
  – mainly along the southern part of the European plate on its section with African, Arab and Indian plates;

– along the section of the European and North American plates;

– in the southern hemisphere:

– mainly along the western and eastern part of the African Plate on its section with South American and Australian plates;

– along the section of the Antarctic Plate with the Pacific, South American, African and Australian plates.

The basis for further scientific research aimed at a comprehensive assessment of the level of seismic hazard of the Earth's territory is the results obtained in this article. Thus, it is planned to assess the degree of interrelation between the main parameters of the Earth's motion in the Sun–Earth–Moon system and the main parameters of tectonic danger of seismically active local territories of the Earth, using the basic multidimensional statistical analysis methods: discriminant, canonical and classification trees.

The research results have practical significance in the field of civil protection of the population and the planet's territory. It is aimed at developing the scientific basis for creating an effective geo-information subsystem for monitoring emergencies of tectonic origin based on the development of neural network prediction models.

4. Conclusions

1. Creating a comprehensive four-level (taking into account the relationships between the facility, city, regional and state levels) automated emergency monitoring system is a prerequisite for establishing an appropriate level of seismic safety of the controlled local territory. This system should include a subsystem for early detection of seismic activity seat and prediction of seismic hazard across the globe. The basis of the subsystem for the early detection of seismic seat and prediction of seismic hazard in a controlled local area is the classic control loop. It provides for the collection, processing and analysis of information, as well as modeling the development of seismic hazard across the globe.

2. The mechanism of the energy influence seasonal fluctuations of the globe core: variations in the speed of the globe rotation axial; the level of seismic activity of the Earth was justified in the development of a systematic approach for predicting the occurrence of emergencies of tectonic origin. Based on the analysis of the variations in the speed of the globe rotation axial and the eccentric uniform translational-rotational dynamic motion of the inner core of the Earth, the possibility of establishing a periodic oscillation of the seismic state of the planet has been considered. Based on the results of monthly variations in the speed of the globe rotation axial and seismic activity on the surface of the Earth relative to the route of its internal core a seasonal redistribution of the energy influence of the internal core on the speed of the globe rotation axial and the level of seismic activity of the seismically unsTable territories of the Earth has been established. Based on the analysis of the processing results number of earthquakes over the surface of the globe an asymmetric distribution of ES of tectonic origin over the surface of the Earth has been established.

3. Using the method of hierarchical clustering of seismically active local territories of the Earth, obtained by dividing maps into detached sheets of 1:1,000,000 scales by the main parameters of seismic activity and by the number of earthquakes and magnitudes in a certain local area ranking has been applied.

As a result, the value of these variables for the period 2009–2018 has been combined in each cluster using the Ward method. The effect of seismically active local areas of the Earth into three main clusters characterizing seismic activity has been established.

4. The combination of the ranked seismically active local territories of the Earth in terms of the hazard level allowed to establish that the zones with a relatively high degree of seismic activity have been revealed: along the section of the European and Pacific plates; around the Philippine Plate; along the section of the North American and Pacific plates; around the Caribbean Plate; along the section of the Australian and Pacific plates; along the section of the South American plate and the Nazca plate. Obtained in this way, zones with a relatively low degree of seismic activity have been located: mainly along the southern part of the European Plate on its section with African, Arab and Indian plates; along the section of the European and North American plates; mainly

along the western and eastern parts of the African Plate on its section with the South American and Australian plates; along the section of the Antarctic Plate with the Pacific, South American, African and Australian plates.

5. The results obtained in this article are the basis for further carrying out a comprehensive assessment of the relationships between the main parameters of the Earth's movement in the Sun – Earth – Moon system and the main tectonic danger parameters of seismically active local territories of the Earth. The subsequent comprehensive assessment is formed using the basic multidimensional statistical analysis methods – discriminant, canonical and classification tree. The use of complex multidimensional statistical methods based on neural network predictive models is necessary for successfully solving the problem of improving the efficiency of monitoring emergencies of tectonic origin.

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CONTROL AUTOMATION OF MARITIME UNMANNED COMPLEX WITH A GROUP OF AUTONOMOUS UNDERWATER VEHICLES

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Abstract

It is expedient to perform underwater search operations on large water areas using a group of autonomous self-propelled underwater vehicles. However, with a large distance to the search areas, the sea transition (from one point to the other) of the underwater vehicles requires high energy costs. This leads to the necessity to use heavy-duty underwater vehicles, which determines the high cost of the search operation. The transport of underwater vehicles is proposed to be carried out with an unmanned surface vessel, equipped with actuators for the automatic release of a group of vehicles under water and receiving on board after the end of the underwater mission. The maritime unmanned complex consisting of an unmanned surface vessel and a group of autonomous underwater vehicles on its board forms a new type of marine robotics, the complete automation of which is an actual scientific and technical task. For its implementation, the underlying (basic) automation technology of the marine search underwater mission has been developed as the theoretical basis for the development of the generalized structure of the complex automatic control system. Ten implementation stages of the underlying technology are formulated and the analysis of their automation features with the use of modern methods in the field of marine robotics is performed. Automation of the underlying technology stages involves the transfer of the vessel to a given water area, the automatic release (launch) of the group of underwater vehicles and their coordinated motion to the search area, the search operations and the return to the unmanned surface vessel, as well as the recovery of the vessel to the base. The generalized requirements for automatic control systems constituting the maritime unmanned complex at each stage of its functioning are provided. The spiral trajectory of waiting for the motion of the underwater vehicles at the group formation stages, for the search operation execution and after its completion, is proposed. For the spatial motion of the autonomous underwater vehicle as an agent of the group, the automatic control system was improved by introducing the blocks of the "Navigation Situation Model" and the "Navigation Threat Identifier, which make it impossible for emergency collision with the neighboring underwater vehicles of the group and disintegrate the group due to the data communication loss between them.

Keywords: maritime unmanned complex, autonomous underwater vehicle, underlying technology, automatic control.

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1. Introduction

Autonomous Underwater Vehicle (AUV) is an effective instrument for carrying out a wide range of marine underwater search missions (exploratory) in nature [1, 2].

However, when performing such operations on large areas of water, the performance of a single AUV is low, which leads to an increase in the duration of underwater missions or even to the failure of their implementation.

One of the effective technologies for conducting unmanned maritime underwater missions is the group application of the AUVs, which guarantees the rapid survey of large areas with minimal time expenditure [3]. With such technology, underwater vehicles have hydroacoustic communication with each other, which ensures their collective operation and its high performance.

However, the transition of the AUVs group to a given water area to carry out their search mission, as a rule, requires an increased resource of their on-board power supplies. This necessitates the use of high-energy AUVs, which increases the total cost of marine search operations.

It is expedient to carry out the delivery of the AUVs group to the search operation area using the unmanned surface vessel (USV). This will eliminate the need for each AUV to perform a long-distance maritime transition to a given search water area; will allow the use of AUV with relatively low energy supply, which is sufficient for maneuvering the USV and performing own underwater search mission.

Thus, to perform the maritime search mission, it is proposed to create a Maritime Unmanned Complex (MUC) as part of the USV and the AUVs group is located on its board.

The main problems of creating such a complex include the determination of its modes of operation and the development of a generalized automatic control system (ACS) of the complex in these modes. In particular, it is necessary to ensure the automatic transition of the MUC to a given point in the water area, the launch of the AUVs group into the sea, data communication with them and returning (recovery) to the USV board after the completion of the underwater search mission.

However, one of the important tasks of automatic control of the MUC underwater mission is to organize a coordinated spatial motion of the AUVs without the contact of neighboring vehicles and without excessively increasing the distance between them, which can cause the disappearance of the connection between the AUVs and the group breakup. Obviously, this task can be accomplished by improving the ACS of the individual AUVs on the account of obtaining additional information about the external navigation environment and the AUVs motion threats that exist in it.

2. Literature review and problem statement

The issue of group control of autonomous vehicles-robots has been highlighted over the past 10 years [4, 5]. The works associated with the use of Multi-Agent Systems (MAS) in maritime environmental and archaeological researches are of particular relevance [6, 7]. At present, the issues of control automation of a group of agents using complex onboard navigation devices and receivers of satellite navigation systems, radio channels, etc., have been rather fully investigated [8–10]. Such systems use multipurpose collaborative search algorithms, adaptive prediction, and wildlife-based algorithms (dolphins, fishes, etc.).

The researchers pay considerable attention to the mathematical modeling of the AUVs group motion processes, in particular, the creation of models of the external underwater environment and the identification of underwater threats, as well as the identification of the AUVs own parameters [11–13].

However, the issue of automation of robotic marine complexes, which ensure operative transportation of AUVs to remote areas of underwater search operations, has not been adequately investigated. In particular, the development of the automatic launch system, of the AUVs group in such water areas are required and their group operation until the full implementation of the search mission.

The aim of the article is to develop the basic tasks of the automatic control of a maritime unmanned complex, which performs the underwater search mission on a large remote maritime water area.

To achieve this goal, the following tasks are proposed to be solved:

– to develop an underlying technology for the automatic execution of marine underwater missions of searching nature with the help of the MUC and to determine its functioning features;

– to improve the ACS of the spatial motion of a individual AUV operating in the conditions of uncertainty of the external underwater environment characteristics by introducing the simulation blocks of external navigation environment and identification of navigation threats.

3. The development results of MUC control automation tasks

3. 1. Development of a basic production technology of marine underwater missions of search nature using MUC

The modern experience of creating and using maritime robotics equipments [14, 15] allows defining the following ten basic stages of implementing the production underlying technology of maritime underwater search missions A_{MUC}:

1 – MUC automatic transition SC_{MUC1} from the port of departure to the designated point of the sea area concerned, where the launch of the AUVs group is planned;

2 – automatic launch of the group from the USV board in the sea RS_{AUV} at a predetermined point of the sea area;

3 – self-organization (automatic formation) of the released AUVs to F_{MAS1} group for collective transition to the working zone, where the underwater mission will be performed;

4 – automatic group transition of the released AUVs T_{MAS1} to the working zone of the predetermined water area;

5 – automatic engagement by each AUV of the group of initial position S_{MAS} for coordinated spatial motion in a predetermined search trajectory;

6 – AUVs group automatic implementation of the underwater search mission to the designated point J_{MAS} (for example: search, identification and mapping of underwater objects);

7 – self-organization (automatic assembly) of AUVs into group F_{MAS2} for return to the USV;

8 – automatic group transition of AUVs to USV T_{MAS2};

9 – automatic return of the AUVs group aboard the USV CS_{AUV}:

10 – automatic transition of MUC SC_{MUC2} to the home port.

Thus, the main stages of realizing the MUC basic task A_{MUC} can be represented by a set:

$$A_{\mathrm{MUC}}=\{SC_{\mathrm{MUC1}};\ RS_{\mathrm{AUV}};\ F_{\mathrm{MAS1}};\ T_{\mathrm{MAS}};\ S_{\mathrm{MAS}};\ J_{\mathrm{MAS}};\ F_{\mathrm{MAS2}}:\ T_{\mathrm{MAS2}};\ CS_{\mathrm{AUV}};\ SC_{\mathrm{MUC2}}\}. \quad (1)$$

Let's now consider the main features of the organization of the MUC controlled motion during the maritime search operation.

The first and the tenth stages ($SC_{\mathrm{MUC1}}\in A_{\mathrm{MUC}}$; $SC_{\mathrm{MUC2}}\in A_{\mathrm{MUC}}$) provide for the USV automatic motion with the AUVs group aboard from the port of departure to the scheduled point of release. Usually, such a transition occurs under conditions of external perturbations – wind and wave influences, flow, the appearance of navigational obstacles, etc. Therefore, the main requirements for the automatic control of USV motion are to ensure the safe motion of the vessel with a given trajectory with the estimated speed. At these stages of MUC mission, the known ACSs, created for the control of the USV can be used [16].

Automatic launch of the AUVs group from the USV board to the sea to the point with the predetermined geographic coordinates of the underwater search start ($RS_{\mathrm{AUV}}\in A_{\mathrm{MUC}}$ second stage) and the automatic return of the AUVs group to the USV after the completion of the underwater search ($CS_{\mathrm{AUV}}\in A_{\mathrm{MUC}}$ ninth stage) are complex scientific and technical tasks. Their solution is possible with the help of the vessel's actuating mechanism of the conveyor type, when for the release/return of the next AUVs from the USV board, a special underwater garage (UG) is lowered. At the same time, the USV is automatically positioned at the point of AUVs release (P_{USV} mode).

The synthesis of such mechanisms and their control systems is a separate applied scientific and technical task and is not considered in this article.

The automatic formation of AUVs released into the group, (third stage $F_{\mathrm{MAS1}}\in A_{\mathrm{MUC}}$) for a collective transition to the working zone, where the underwater mission will be performed, forms a separate scientific task. The peculiarity of the automatic control of the search mission indicated stage is the need to move the AUVs along special trajectories of waiting. Such trajectories should provide for the content of the first released AUVs in the group in the process of releasing the next batch of underwater vehicles. It is advisable to first perform the release of the AUV-leader, which will form the trajectory of waiting.

When forming a plane (two-dimensional) AUVs group, such trajectories may take the form of an Archimedes spiral, diverging from the spiral pitch $a \le r_C$, where r_C is the range of the AUVs underwater communication system.

When forming a bulk (three-dimensional) AUVs group, the trajectory of waiting may take the form of several such spirals located at predetermined depths.

In the first case, when using the actuating mechanism of the conveyor type, the vessel's ACS, which controls the release of underwater vehicles, must carry out the release of AUVs with time interval:

$$\Delta t = {s_{\mathrm{AUV}}}/{v_{\mathrm{AUV}}}, \quad (2)$$

where $d < s_{\mathrm{AUV}} < r_C$ is the segment of the spiral trajectory of the released AUV; d is the minimum safe permissible distance between neighboring AUVs; v_{AUV} is the linear motion velocity of the released AUV.

When applying the AUV release mechanism of the cassette-type, the group of the underwater vehicles falls into water at the same time.

In the second case (the formation of the three-dimensional AUVs group), the vessel's ACS should begin to form the AUVs spiral trajectories of waiting from the highest given depth and complete the minimum predetermined depth.

In this case, the ACS of each released AUV must provide its plane motion along the Archimedes' spiral with a pitch $a \le r_C$.

Group transition of the released AUVs. It is advisable to carry out a group transition of the released_AUVs to the working zone of a predetermined water area (the fourth stage $T_{\mathrm{MAS1}} \in A_{\mathrm{MUC}}$)) immediately after the release of the last group AUV. The beginning of the motion of each underwater vehicle in the group at a given depth of H_{MAS1}, given course φ_{MAS1} and with a given speed v_{MAS1} should be a common team, which is drawn from the USV ACS or from the AUV-leader [17]. One of the main tasks of the automation of this maritime search mission phase is AUVs coordinated motion without loss, i. e. without the collision of the neighboring underwater vehicles (vehicles excessive close approach) and without losing the connection (communication) between them (vehicles excessive distancing).

The automatic occupation of the initial position by each of the AUV (fifth stage $\mathrm{S}_{\mathrm{MAS}} \in \mathrm{A}_{\mathrm{MUC}}$) for the coordinated spatial motion on the predetermined search trajectory is performed in accordance with the survey plan of a given water area, which has been pre-drawn up and entered into each AUV ACS. At the same time, lossless motion should be provided – avoiding AUVs collisions and removing beyond the limits of underwater communication systems operation.

The AUVs group automatically performs the underwater search mission (sixth stage $J_{\mathrm{MAS}} \in A_{\mathrm{MUC}}$) by the AUVs group coordinated motion to specified trajectories [18]. Navigation support for this mission stage can be organized using a bottom navigation system, pre-installed in the search area, or using navigation AUVs, equipped with GPS devices to determine own geographical coordinates, and hydroacoustic systems navigation support of underwater operations [19].

An important component of automatic control of this mission phase is also the AUVs group motion without collisions and loss of communication between the vehicles.

The AUVs automatic assembly into a group after the completion of the search operation to return to the USV (seventh stage $F_{\mathrm{MAS2}} \in A_{\mathrm{MUC}}$) is performed by the AUV- leader's command. In the course of its implementation, the trajectory of waiting is formed by analogy with the third stage.

After collecting the full AUVs group, by the AUV-leader's command, starts the *group transition to the USV* ($T_{\mathrm{MAS2}} \in A_{\mathrm{MUC}}$). The motion of each underwater vehicle in the group at a given depth of H_{MAS2}, at a given course φ_{MAS2} and at a given speed v_{MAS2} should be without loss – without collisions of neighboring vehicles and without loss of hydroacoustic communication between them.

The underlying technology for performing maritime underwater missions of a search nature with the help of MUC, taking into account the main modes of its operation, can be presented in the form of the algorithm shown in **Fig. 1**.

In **Fig. 1** the marked symbols $Y1...Y10$, are the conditions for the stages implementation (1) of the implementation of the MUC basic task A_{MUC} (x_1 is the planned progress of the implementation of the mission adequate phase; x_2 is the planned completion of the mission corresponding phase, x_3 is the unplanned stage progress, requiring access to the MUC ACS of higher level (transition **B**).

Other symbols on **Fig. 1** correspond to (1).

The obtained algorithm can serve as the basis for the synthesis of the generalized structure of MUC ACS when performing underwater search missions.

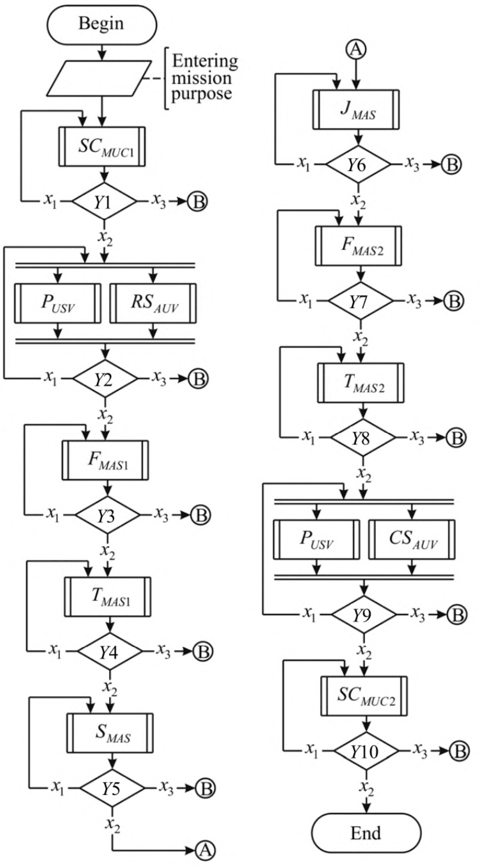

Fig. 1. The underlying technology of the search for maritime underwater missions using the MUC

3. 2. Synthesis of ACS of individual AUV spatial motion as a group agent

Further, we will consider the plane motion of a single AUV as a group agent during the execution of the stages T_{MAS1} and T_{MAS2}, as typical for organization of group motion in conditions of uncertainty in the characteristics of the external underwater environment. These uncertainties include the presence of neighboring AUVs that create navigation obstacles (in particular, the threats of collision during the group motion).

The AUVs group control tasks analysis at the specified stages of the maritime mission implementation indicates that one of the key tasks is ensuring the safe (trouble-free) motion of the individual AUVs in the group at a given depth of H_{MAS}, at a given course φ_{MAS} and at a given speed v_{MAS}. The theoretical basis for the automation of such motion A_{MUC} is the notion of alignment A_{GU}, adhesion A_{GA} and cohesion A_{GC} [20].

The concept of alignment implies the observance of the above three mentioned parameters of

$$A_{GU}=\{\varphi_{\mathrm{MAS}};\, v_{\mathrm{MAS}};\, H_{\mathrm{MAS}}\}, \tag{3}$$

which requires the AUVs group motion in a given direction or a given spatial trajectory and automatically control the motion of an individual AUV as a group agent in a given direction with the recommended given speed and at a given depth, which is the same for all the group AUVs.

The concept of adhesion involves the task of each AUV as a group agent to move with the consideration of A_{GU} and simultaneously control the minimum possible distance between an individual agent and its neighbors, which is safe from a collision point of view:

$$A_{GA}=\{x_i \geq x_{\min} \big|_{i=1,\ldots S}\}, \tag{4}$$

where x_i is the distance from its AUV to the neighboring AUV at the course angle i; $x_{\min}$ is the minimum safe distance to the neighboring AUV; S is the number of course angles controlled by the appropriate navigation range finders of its AUV.

The concept of cohesion involves the task of each group agent to move with regard to A_{GU} and simultaneously controlling the maximum possible distance between an individual agent and its neighbors, safe from the point of view of loss of sensory contact (for example, hydroacoustic communication) and, consequently, the loss from the AUVs group as a result of its "dispersion":

$$A_{GC}=\{x_i\leq x_{\max}\,|_{i=1,\dots S}\}, \tag{5}$$

where $x_{\max}$ is the maximum allowable distance between its AUV and the neighboring AUV, which maintains a reliable sensory contact between the vehicles.

Hydroacoustic, laser, or electrical sensors may be used as the AUV rangefinders, which should provide the underwater vehicle automatic control system sensitivity to neighboring AUVs moving in the group [21, 22].

The number of sensors and their directional patterns depend on a number of requirements in the AUVs group motion and on the performance peculiarities of the search underwater mission. Typically, the number of sensors varies from 4 to 12 and provides measurements of distances between the AUVs at the corresponding angular angles of the ranges from 0.1 m to 20 m, which makes it possible to build efficient group motion control systems.

It is obvious that when performing the general requirement (3) in order to avoid collisions with the neighboring AUVs, our underwater vehicle has two main types of maneuvers - course maneuver and speed maneuver. Depth maneuver will be considered an emergency, undesirable in terms of the mission.

For the evaluation of the degree of collision threat between the AUVs group agents, it is suggested to include in the ACS for each AUV the special blocks – the "Navigation Situation Model (NSM)" block around the appropriate AUV and the "Navigation Threat Identifier (NTI)" block for this AUV. It is expedient to build these blocks using the theory of fuzzy logic [23]. Consider the purpose of these blocks in more detail.

The main idea of the NSM formation for a specific AUV is to formulate, for its AUV, the current underwater navigational situation with the definition of the nearest AUV-neighbors, which form the threat of collision from the controlled S directions, and to determine the distances to them $X=\{x_1;\dots x_S\}$.

The task of the NTI block is to determine the dynamic parameters of the motion of the detected AUV-neighbors and to quantitatively calculate the level of danger of a collision or loss of contact with it (the characteristics of adhesion and cohesion of its AUV with respect to the nearest AUV-neighbors).

The generalized ACS structure of a single AUV as a group agent is shown in **Fig. 2.**

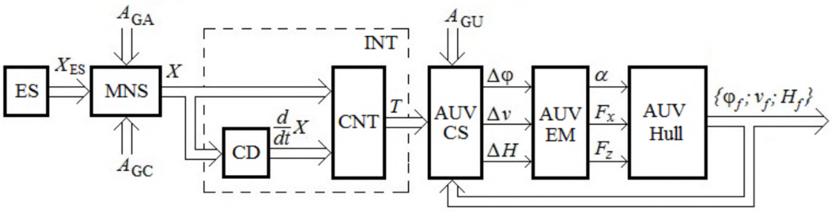

Fig. 2. Generalized ACS structure of a single AUV as a group agent

Consider the basic principles of operation of the above ACS.

The environment sensor (ES) block contains a set of N group motion sensors $X_{ES}=\{X_{ES1};\dots X_{ESi};\dots X_{ESN}\}$ sensors with the targets which are shown in their measurement sectors). At the exit of the ES block, multiple sets of distances are formed to the neighboring AUV, and each set of signals X_{ESi} may contain several distances, if there are several AUV-neighbors in the i-th sensor measurement sector. The course angles on such targets are determined by the arrangement of the corresponding sensor on the AUV hull in the linked coordinate system [24].

The X_{ES} signal-based NSM block forms the targets current static picture around its AUV and defines N closest AUV-neighbors that form the greatest threat of collision for it, and calculates the distances $X_{ES}=\{X_{ES1};\ldots X_{ESi};\ldots X_{ESN}\}$.

The NTI threat Identification block evaluates the degree of collision threat with the AUV-neighbors and/or the threat of losing contact with the AUVs group in the event of a horizontal maneuver according to dependencies (4), (5), and also calculates a forecast of the group motion dynamics identified by AUV-neighbors. The NTI block contains a module for calculating the derivative distances of identified targets (Calculus of Derivative, CD) and navigational threats calculator (Calculus of Navigation Threat, CNT), which is proposed to be built on the basis of fuzzy logic [23]. The output signal of the NTI block is a recommendation vector for maneuvering in order to avoid threats $T=\{T_1;\ldots;\ T_i;\ldots;\ T_N\}$, where $T_i=f(\varphi_i;\ v_i;\ H_i)$ is a recommendation on the maneuver of its AUV to avoid collision or intolerable removal from the i-th AUV-neighbor.

The AUV automatic control system (AUV ACS) summarizes the calculated recommendations, using them as corrective signals for generating control actions $\{\Delta\varphi;\ \Delta v;\ \Delta H\}$ on the AUV actuating mechanisms (Executive Mechnism, EM) – the steering wheel is steered (the controlled value is the rudder angle α), the marching propulsion device (the controlled value is the thrust on the longitudinal axis Fx) and, in emergency cases, its vertical propulsion device (the controlled value is the thrust on the vertical axis Fz).

The aforementioned control influences applied to the AUV hull, cause the appearance of the actual variables of the spatial motion of our AUV – $\{\varphi_f;\ v_f;\ H_f\}$, which are used as feedback signals in the automatic control system of the underwater vehicle, AUV ACS.

4. Discussion of the development of MUC control automation tasks

Group application of AUV provides high performance underwater search operations. However, when it is necessary to perform an underwater search in remote areas, its performance is significantly reduced, since underwater vehicles have to travel long distances to move from the base to the place of work. Therefore, a maritime unmanned complex consisting of an unmanned surface vessel and the AUVs group on board is promising equipment for carrying out prospecting operations in such water areas.

The development of the automatic control system for unmanned surface vessels as the carrier of the AUVs group and the automatic control system for the AUVs group motion during the execution of the search mission are among the actual tasks of the MUC. For their synthesis, it is necessary to perform an analysis of the main stages of the MUC and determine the features of the AUVs group application, which are produced from the board of such a vessel.

The underlying technology proposed in the article for performing marine underwater missions of a search character with the help of an MUC forms the theoretical basis for the development of the generalized structure of the automatic control system of the MUC. It contains a description of the complete set of stages of the complex operation and analysis of the peculiarities of their automation, using modern advances in the field of marine robotics.

Based on the analysis of uncertainties that occurs during the AUVs group motion, the need to improve the automatic control system of a single AUV as an agent of the group has been shown. It was proposed to introduce into its structure the block "Navigation situation Model" and the block "Navigation threats Identifier", which will exclude the threat of an emergency collision of the groups neighboring AUVs and the disintegration of the group due to the loss of communication between the AUV. At the same time, the AUVs group motion is preserved by a given course at a given depth.

Cumulatively, the obtained theoretical results allow us to further formulate the tasks of automatic control systems synthesis for individual stages of the MUC and modes of operation of its executive mechanisms, as well as synthesis for control systems for safe spatial motion of an AUV as an agent of the group.

5. Conclusions

To improve the performance of underwater search operations in remote marine areas, it was proposed to use an maritime unmanned complex as part of an unmanned surface vessel with a group of autonomous underwater vehicles on board. The relevance of the applied scientific task of control automation of such a complex is shown, as well as the need to improve the automatic control system of an individual AUV as an agent of the group, working in conditions of uncertainty.

An underlying technology has been developed for performing a marine underwater search mission with the help of the MUC as a carrier of a group of autonomous uninhabited underwater vehicles. It envisages ten stages, which generally cover the operations of automatic transition of the MUC to a given water area, automatic release of the AUVs group and their coordinated movement to the search area, performing search operations and returning to the unmanned surface vessel, as well as automatically returning the vessel to the base.

The peculiarities of the application of the MUC are considered and the generalized requirements for the automatic control systems of the components of the MUC at each stage of its operation are provided. In particular, the proposed spiral ‘trajectory of waiting’ for AUVs that are in the water, during the implementation of the formation stage of the AUVs group and the collection stage of the individual AUVs into the group after the search operation is completed.

The automatic control system of the spatial motion of an individual AUV, which performs the sea transition as part of a group and operates in conditions of uncertainty, has been developed. It was proposed to introduce into the control system the blocks “of the Navigation Situation Model” and the “Navigation Threats Identifier”, which make it impossible for an emergency collision of the neighboring AUVs groups and the disintegration of the group due to the loss of information communication between the AUVs.

Further automation of the MUC with the AUVs group is seen in the control systems synthesis for executive mechanisms of unmanned surface vessels and in the synthesis of the blocks “Navigation Situation Model” and “Navigation Threats Identifier” of the AUV ACS.

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METHOD OF PROTECTING SPECIALLY IMPORTANT OBJECTS BASED ON THE APPLICATION OF THE BISTATIC RADIOLOCATION TECHNIQUE

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Abstract

The solution of the tasks assigned to the National Guard of the state implies the presence of certain forces and means with the appropriate technical equipment. A well-known place among such tasks is security of important state facilities. Various physical effects and methods, including radar, are used to create security systems.

The development of radar technology and technology made it possible to increase both the quantity and quality of the received information, as well as the use of radar stations for observing living objects.

The industry today produces bioradioradars for detecting people and controlling their movements. All samples are made in a single-position version and have a relatively high cost, the fact of their work is easily detected, which facilitates their suppression, including force.

In order to increase the secrecy of work, it is proposed to use the methods of separated, more precisely, bistatic location to control the area in front of particularly important objects.

The defining detection index is the effective reflective surface (ERS), which is about 1 m2 for a person. Equipment, weapons and protective equipment contributes to the increase in the ERS.

Given the small reflective surface of biological objects, it is proposed to limit the area of responsibility to the sector form in which, at a certain bistatic angle, the effect of a significant increase in the signal/(interference+noise) ratio is manifested. For a specific definition of the gain, it is necessary to choose the operating frequency of the bistatic system and its geometry.

For greater secrecy, it is advisable to use the transmitters of radio and television broadcasting, mobile communications, etc. The estimates found, for example, when using digital television transmitters (T2), indicate that the creation of a secretive bistatic system is quite possible – at least in a geometric interpretation.

Keywords: biolocation, bistatic RLS, bistatic angle, terrorism, effective reflective surface.

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1. Introduction

The issues of ensuring the security of various objects, first of all – especially important state ones, are highly relevant. One of the most important elements of almost any security system (informational, anti-terrorist, anti-criminal, etc.) is a physical protection complex (PPC). For the detection of unauthorized entry of the intruder, they usually use an alarm system as one of the important components of the PPC [1].

In developing and analyzing the effectiveness of such systems, the primary goal is achieving the required detection efficiency of the intruder. Efficiency increases with an increase in the residence time of the intruder in the zone. This implies the conclusion that it is necessary to increase the range of target detection in order to increase the response time. In solving this problem, it is necessary to take into account not only the specifics of choosing the type and location of detection tools (DT), but also possible methods of influencing the DT of a qualified intruder who has a priori knowledge of the principles of operation and parameters of the means, which reduces the possibility of its detection. In other words, it is necessary to hide the operation of the detection tool.

Various physical effects and methods are used to create security systems [2] – video and radar surveillance, perimeter security systems, security and fire alarm systems, and access control systems. Each system has its advantages and disadvantages. Let's note that further considered systems using only radar methods.

The development of radar technology and technology made it possible to increase both the quantity and quality of the information received, as well as the use of radar stations for observing living objects.

The industry today releases radars to detect people and control their movements. All samples are made in a single-position version and have a relatively high cost, the fact of their work is easily detected, which facilitates their suppression, including force.

In order to increase the secrecy of work, it is proposed to use the methods of separated (more precisely, bistatic) locations to control the territory remote from especially important objects.

For greater secrecy, it is advisable to use the radio and television broadcasting transmitters, mobile communications, etc. operating in the territory in question. Even if the offender has information about the presence of such a system, the fact of its functioning cannot be determined. Therefore, for example, let's find estimates, for example, when using digital television transmitters (T2), confirming that the creation of a secretive bistatic system is quite possible – at least in a geometric interpretation.

The defining detection index is the effective reflective surface (ERS), which is about 1 m^2 for a person. Equipment, weapons and protective equipment contributes to the increase in the ERS.

Given the small reflective surface of biological objects, it is proposed to determine the shape (circular, sector) areas of responsibility, in which, at a certain value of the bistatic angle, the effect of a significant increase in the "signal/(disturbance+noise)" ratio appears. For a specific definition of the gain, it is necessary to choose the operating frequency of the bistatic system and its geometry.

2. Literature review and problem statement

The continued development and intensive introduction of short-range radar methods indicates an expansion of their areas of application. They are used to develop systems for protecting important objects from intruders and blocking terrorist acts. Under these conditions, the object will be the person, i. e. biological object [2]. The tasks of the National Guard of many countries include the following:

– protection of objects protected by the National Guard (NG);

– prevention of the activities of illegal militarized or armed groups (formations), terrorist groups and criminals;

– participation in antiterrorist operations;

– participation in actions related to the cessation of armed conflicts and other provocations at the border, as well as in measures to prevent mass violations of the state border from the territory of neighboring states.

Similar tasks arise in states when it is necessary to ensure the security of a protected area. An example would be the protection from the infiltration of saboteurs on military bases (airfields in Syria), the advancement of terrorist groups into enemy territory in the Iran-Israel conflict, etc.

Let's consider briefly the characteristics of fixed assets represented by industry.

Currently, Ukraine uses radio location stations (RLS) for reconnaissance of ground targets 112L1 "Barsuk" (**Fig. 1**) and a station to monitor ground and low-speed low-flying targets 111L1 "Lis" (**Fig. 2**).

The radars 111L1 and 112L1 detect moving targets and equipment to ensure the protection or reconnaissance of the territory. "Barsuk" is wearable radar that provides detection of people, ground and surface transport objects [3]. The locator is built according to the classical active principle, in which significant power consumption from the power source (and cost) is determined by the presence of a transmitter, without which radar operation is impossible. "Barsuk" is used to detect moving people and equipment, to reconnoiter and ensure the protection of the territory [4], but it cannot detect fixed targets.

Fig. 1. "Barsuk" locator

a *b*

Fig. 2. "Lis" locator :
a – general view of the locator on the platform; *b* – under the hood on the car

Both radar continuous radiation, which allows the use of a transmitter with a very low radiation power – 200 mW and (30...40) mW, respectively. They operate in the millimeter wavelength range, the frequency is about 36 GHz.

Radars automatically detect objects and measure the distance to them at any time of the year, in case of bad weather – rain, dust, fog and no optical visibility. Target detection range with a radial speed of 2–50 km/h for the "Barsuk": a single person 600...800 m, vehicles – up to 1600 m. The same indicators for the "Lis" are a single person – 5.4 km, car, motor boat – 11.5 km, helicopter – 12 km. Marked characteristics will take as the source for later use.

"Jeb" equipment is mounted on a mobile chassis [5], which is not at all necessary for the protection of important stationary objects. In addition, to solve the tasks of observation in the area of the Jeb object, it is over-equipped with EW equipment, which increases the cost of manufacture and operation. Marked funds mastered in Ukraine.

The development of short-range radar is carried out in Russia – let's note the radar complex to monitor the situation in the zone of objects "Radeskan" [6]. In the complex "Radeskan" two working frequency ranges are used – video and radio, but the latter is characterized by the presence of special radiation, which is easily detected by the enemy to carry out counteraction.

Similar developments are carried out in different countries – AN/PPS-15, "Fallen", "Astrid" (USA), "Arabelle" (France), "Permagard" (Great Britain), "Isidore" (Sweden) [7, 8]. These radars provide a solution to a wide range of tasks, including locations and important objects along the perimeter, the ability to detect a moving person. For existing funds remain unresolved until the end of the task of increasing the range and accuracy of target detection, reduction of false positives (work behind the foliage of trees).

The common shortcomings of all ground reconnaissance radars include the detection of their work by the enemy at distances far exceeding the range of these radars. In addition, there is a large exposure to the effects of electronic suppression of the enemy.

When radar probing, traditional objects of location until recently were mostly non-living objects (targets), most often airborne [9, 10].

Thus, traditionally used monostatic radars for detecting moving objects in such conditions are ineffective due to the large number of interfering reflections (forest, buildings, rugged terrain) and low speed of movement of detected objects (people). The use of several such radars is impractical because of their relatively high complexity and cost. In addition, it is impossible to ensure the *secrecy of such detection systems*, which is an important condition for radar surveillance.

Currently, the so-called MIMO (Multiple Input Multiple Output) systems are being developed in radiolocation. This definition includes systems that have multichannel receiving and/or transmitting systems that use one of the methods for separating signals in channels, and joint processing of these signals is performed. The application of the principles of MIMO systems in the construction of multi-position forward-scattering RLS is a promising, but poorly understood direction.

For the described conditions, the construction of radar observation systems in the form of a forward-scattering multi-position (in particular, two-position, bistatic) radar system seems promising. The primary field in semi-active systems is created by the transmitter, which is not included in this system and is an external element with respect to it. In this case, the only element of the system itself is the receiver, but it functions in close cooperation with the transmitter external to the system.

An analysis of technical literature [3–10] shows that the use of the principles of separated (semi-active) radar for covert observation of biological objects in scientific periodicals is practically not discussed. Therefore, let's further consider how methods and means of biolocation can be implemented by separated systems.

Solving problems related to the research and development of ground-based radar detection of ground targets is of great scientific importance and should allow such systems to be used to solve problems of detecting, locating and classifying moving ground objects under the influence of passive interference, including from vegetation. This determines the relevance of the article.

Currently, the so-called MIMO (Multiple Input Multiple Output) systems are being developed in radiolocation. This definition includes systems that have multichannel receiving and/or transmitting systems that use one of the methods for separating signals in channels, and joint processing of these signals is performed. The application of the principles of MIMO systems in the construction of multi-position forward-scattering radar is a promising, but poorly understood direction.

Thus, the use of existing and newly developed means of protection of particularly important objects can ensure reliable and timely confrontation. Ensuring security in the immediate vicinity of the perimeter of the object is no longer a problem. At the same time, the issues of observing living objects in emergency conditions – covert surveillance of gangster or terrorist groups hiding on the ground at a considerable distance from the object, remained unsolved until the end.

Let's note that the limitations of the radar detection equipment with continuous radiation, adopted in the article, are explained by the intended use of the external over the illumination system from industrial radio and television broadcasting stations, which operate in continuous mode and thereby ensure the complete secrecy of the target illumination.

The aim of research is in identification of the possible ways to monitor biological objects using bistatic RLS methods. In addition, from geometric positions it is supposed to evaluate the possibility of implementing the "forward-scattering" mode on the example of the use of radiation from the transmitter of a digital television system based on land.

To achieve the aim, the following objectives are set:

– to ensure covert and early detection (in comparison with existing norms) of the fact of the infiltration of violators into protected areas;

– to monitor the movement of potential intruders, including on vehicles, in the direction of protected objects to issue a transition signal to high alert;

– taking into account the existing location of radio-emitting centers, determine rational geometry in open areas to achieve maximum responsibility based on the technical characteristics of the light sources.

3. Application of bistatic location methods for the detection of biological objects

By definition, a biolocation is a method of non-contact detection and diagnosis of people (animals), including behind opaque walls, based on the modulation of a radar signal by movements (movements) of a biological object.

Biolocator systems appeared as a result of work at the interface of radiophysics and biology – sciences far from each other. However, researchers have become interested in these systems, and then potential consumers in many countries around the world. The progress of radar technology and technology has allowed many times to increase both the quantity and the quality of information received from the facility, as well as the use of radar stations to monitor living objects.

The range of recorded movements determines the use of electromagnetic waves in bioradiolocator (BRL) up to a very high frequency range. Both emitted and continuous signals with complex modulation can be used as emitted. It is possible to use monochromatic signals.

Information received from biolocator systems can be used to supplement the information necessary for reliable operation of existing information management systems.

For BRL, the following technical characteristics are essential:

– autonomous food and operating time in this mode;

– ability to manually move the device, its weight and dimensions;

– ease of use and ease of image analysis;

– possibility of angular scanning of the area;

– time to detect a stationary (if possible) and a moving person;

– maximum allowable width of the barrier through which it is possible to still find a person;

– maximum distance to which a biolocator can detect a person;

– accuracy of determining the location of the person.

The above data indicate the operation of radio equipment in different frequency ranges. Let's note that when choosing the working range of wavelengths, it is necessary to take into account the general requirements for biolocators, the main of which is the detection range – this information is given in **Table 1**.

This shows (**Table 1**) that, firstly, biological objects can be targets. Secondly – ground and air vehicles (low-flying unmanned aerial vehicles for various purposes). A detailed description of the latter is beyond the scope of the issues addressed. Further consideration will be carried out specifically for biological objects, i. e., humans.

Table 1
Required detection range of ground targets

Radars (range)	Detection range		
	people		vehicle
	going	crawler	
Closer	130–1600	80–300	2000–3000
Small	1500–5000	200–500	5000–10000
Medium	4000–14000	up to 2000	12000–25000
Long	15000–26000	up to 7000	30000–60000

Let's note that a person, like any other target, is characterized, first of all, by the so-called effective reflecting surface (ERS). According to many sources, the reflecting surface is about 1 m^2.

If a person is put on a metal helmet, special shoes and equipment in the form of body armor, bullet-proof linings and plates, its image intensifier will increase significantly as equipment is equipped.

A further increase in this indicator is associated with equipping the fighters with metal rifle armament – an automatic rifle, a grenade launcher, a pistol and ammunition in the form of spare automatic horns, grenades and pistol holders. It is also necessary to take into account the presence of knives, optical and night vision devices, radio communications and navigation.

The task of single-station (monostatic) implementation of the detection of biological objects has now been successfully solved. The authors of these lines could not find any mention of another method - multi-position (in the simple case – bistatic) radar. Therefore, further briefly fill this gap. According to foreign experts [11], bistatic RLSs can be considered as cells of the MPRLS.

In practice, the following (already classical) formulation of the problem is most often considered [12, 13]. A coherent multi-static system consists of several transmitters and several receivers located separately at some distances. Transmitters with their signals should cover all monitored areas. Synchronization between individual transmitters or transmitters and receivers is not required, but it is necessary to know the exact position of both transmitters and receivers.

Of particular interest is the use of transmitters external to the planned radar system as sources of illumination. Such transmitters can be terrestrial and space-based radio and television transmission centers operating with analog and digital (which is better) signals, radio navigation system transmitters, etc. At the same time, the new system acquires undoubted advantages:

– eliminates costly transmitting device locator, because "free" radiation from other industrial systems is used;

– as a consequence of the first, the power consumption of the entire system is significantly reduced, since the main consumer is the transmitter;

– provides almost complete secrecy of the functioning of the new system, because the radiation of a specialized transmitter is excluded, and to detect the radiation of the heterodyne of the receiver, a significant increase in the sensitivity of the reconnaissance receiver of the opposing side will be required;

– a significant (almost all) part of the constituent elements of the new system can be built on the developed and widely manufactured products of the industry, which also reduces the development costs of the system many times.

The decisive role is played by the angle β between the directions from the transmitting and receiving positions to the object, which is called bistatic (**Fig. 3**). This is one of the main geometrical characteristics of bistatic RLSs [14, 15]. With moderate values of the bistatic angle β, according to the "equivalence theorem" and experimental data, the bistatic ERS σ_b is usually close to the one-position ERS of the same target σ_0 (taking into account the averaging over possible angles). However, as the angle β approaches 180°, the picture changes dramatically. Let's consider this circumstance in more detail.

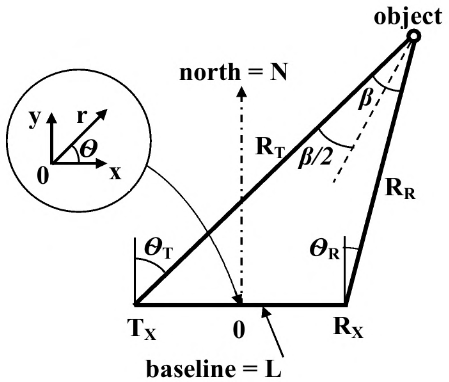


Fig. 3. Bistatic coordinate system for two positions: N – north direction; L – baseline; T_X, R_X – standing points of the transmitter and receiver, respectively; x, y – rectangular coordinate system; θ_T, θ_R – azimuth to the target from the transmitter and receiver; R_T, R_R – transmitter-target and receiver-target distances; β – bistatic angle

For example, for an ideally conducting ball with a radius r_c=20λ (λ is the wavelength), the single-position σ_o and bistatic σ_b at angles β less than 140...150° are 400 $\pi\lambda^2$. When scattering forward, the bistatic ERS is $\sigma_b(180°)=4\pi^3 \cdot 10^4 \cdot \lambda^2$. Therefore, σ_b (180°) is approximately 16,000 times, or 42 dB more. The sharp increase in the ERS of targets in the scattering of forward allows in certain conditions to reduce the energy potential of the radar. It is especially important that the "shadow" ERS σ_b simply can't be reduced [12].

In two-position (bistatic) radio location systems systems (BRLS) situations arise when the target can be observed within a narrow zone adjacent to the base of the system, i. e. the line between the receiving and transmitting positions of the system [16].

If in the path of the wave propagation place an absolutely certain body of large size compared to the wavelength, then a so-called stray field ("shadow" field) will appear behind the body. This field does not depend on the shape of the body surface and is completely determined by its illuminated external boundaries [17]. As a result, a sharp increase in the bistatic σ_b effective dispersion zone (EDZ) of objects is observed. This allows the same time to reduce the requirements for the energy potential of the radar at the same range.

Let's note that the magnitude of the "shadow" EDZ is not affected by radio-absorbing coatings, which are used to impede the location of airplanes and other objects.

Let's consider the characteristics of target detection in these conditions.

The EDZ dependence $\sigma_b(r)$ on the distance r in the far zone at bistatic angles β close to 180° is determined by the following expression, where A_t – the "radiating" aperture [2]:

$$\sigma_b(r) = \frac{4\pi}{\lambda^2} \cdot \left| \int_{A_t} \exp\left[j\frac{2\pi}{\lambda}\rho r \right] \right|^2, \tag{1}$$

here ρ – radius vector of an arbitrary point of the aperture A_t; λ – wavelength; r – ort, directed to the receiving position. The origin is in the conditional center of the aperture A_t.

From (1) it is seen that at β=180°, when r=ρ, EDZ σ_b reaches its maximum:

$$\sigma_b(180°) = 4\pi\left(\frac{S_t}{\lambda^2}\right). \tag{2}$$

In this expression, S_t – area of the aperture A_t. Imagine (2) in the form

$$\sigma_b(180°) = G_t \cdot S_t, \tag{3}$$

where by $G_t = 4\pi\frac{1}{\lambda^2}$ – the directional coefficient of the common-mode aperture A_t with area of S_t. It can be seen that the EDZ σ_b of direct dispersion is greater than the geometric area of the aperture A_t by G_t times. Let's note in passing the condition under which we can expect a significant increase in bistatic EDZ:

$$S_t >> \lambda^2. \tag{4}$$

Fulfillment of this condition directly indicates the choice of the working wavelength and provides (for large compared with the wavelength dimensions of the object) $G_{t>>1}$ and $\sigma_b(180°)>>S_t$. Therefore, the EDZ $\sigma_b(180°)$ is much larger than the single-position EDZ σ_0. With a large excess of $\sigma_b(180°)$ over σ_0, a significant gain in the EDZ can also be maintained in the region of the side lobes of the DN of the aperture A_t.

At the same time, the EDZ σ_b, defined by (2), is preserved only in a relatively narrow sector around the base between the transmitting and receiving positions. For a specific definition of the gain, it is necessary to choose the operating frequency of the bistatic system and its geometry.

For example, let's select the decimeter wavelength range (500...800 MHz, λ=0.6...0.37 m), in which the transmitters of digital television of the T2 format operate. The location of the transmitters on the ground will be tied (also for example) to the Kharkiv region (Ukraine), then the size of the base can vary within 10...90 km. These values are selected according to the location of T2 transmitters in the Belgorod Region (Russian Federation) [18] and are shown for two (randomly selected) stationary points of receivers – in Zolochiv and Vovchansk (Ukraine). However, the number of receiving channels remains unclear – the use of illumination from all transmitters is likely to be redundant, and the very possibility of illumination needs to be determined. The latter is easily estimated by the well-known relationship [19]:

$$D_{ILL} = 3{,}57 \cdot \left(\sqrt{h_{TR}} + \sqrt{h_{OB}}\right). \tag{5}$$

In this formula, h_{TR} and h_{OB} are the height of the transmitter antenna and the height of the object, respectively. Many formulas use a coefficient of 4.12, which is suiTable for *meter* waves. In the formula (5), a factor of 3.57 is used, since waves above 1 GHz are practically not subject to refraction, and therefore do not penetrate beyond the horizon.

Using computer technology, for clarity, let's obtain a graph of dependence (5), presented in **Fig. 4**, for three standard antenna heights.

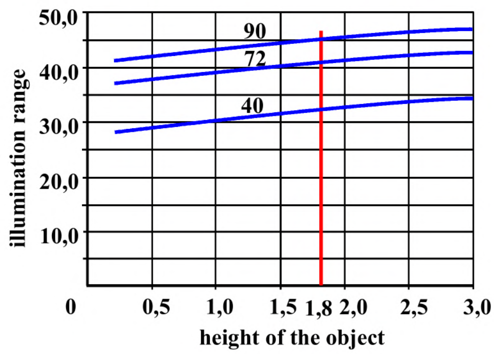
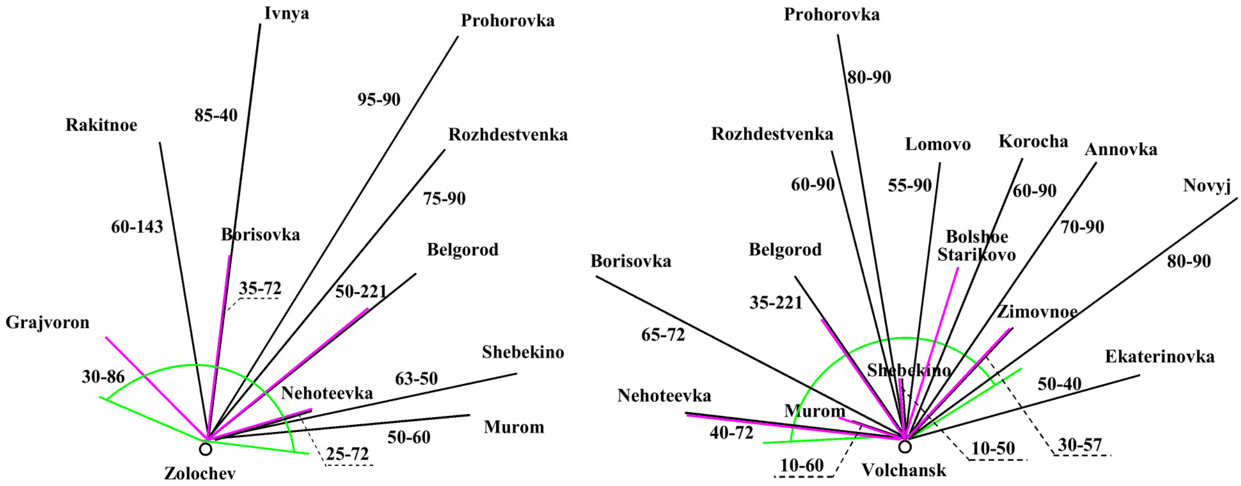


Fig. 4. Dependencies of the illumination range on the heights of the antenna and the object. The red line marks the height of the object – 1.8 m

From the analysis of the curves (**Fig. 4**), it can be seen that for the existing standard antenna suspension heights of the transmitters, the illumination range is 30...45 km, which is shown in **Fig. 5, *a*, *b*** is highlighted with *pink lines*. **Fig. 5, *a*** corresponds to the location of the receiver in Zolochiv, **Fig. 5, *b*** – in Vovchansk. The location of the names of settlements corresponds to the geographical map of the region. Recall that Zolochiv and Vovchansk are located in the northern part of Ukraine, and all other locations on the map are in the Russian Federation.



a *b*

Fig. 5. To the selection of Illumination transmitters: *a* – with a receiver in Zolochiv, *b* – with a receiver in Vovchansk. Numbers 00-00 mean: the first is the distance to the transmitter, the second is the height of the antenna suspension. Green shows service sector at receiver location

Let's now define the geometric relations and conditions for providing the specified – at least 150° – bistatic angle values. For simplicity, considering the surface of the Earth to be flat and using **Fig. 6**, simulating the motion of an object in a straight line *OB* at an angle γ, measured from the line of the base *OA*, let's obtain the following relations.

Let's find the third side:

$$AB=\sqrt{OB^2+OA^2-2\cdot OB\cdot OA\cos\gamma};\tag{6}$$

and the desired bistatic angle:

$$\beta=\arccos\frac{OB^2+AB^2-OA^2}{2\cdot OB\cdot AB}.\tag{7}$$

Let's find, ultimately, the width of the signal reception sector, in which the EDZ is increased by at least 20 dB. This value will be used for the subsequent assessment of the energy performance of a bistatic system with a particular source of external illumination. The calculation results are shown in **Fig. 7** for the three values of the bases – 10, 30 and 50 km.

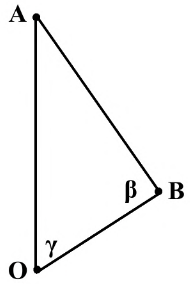
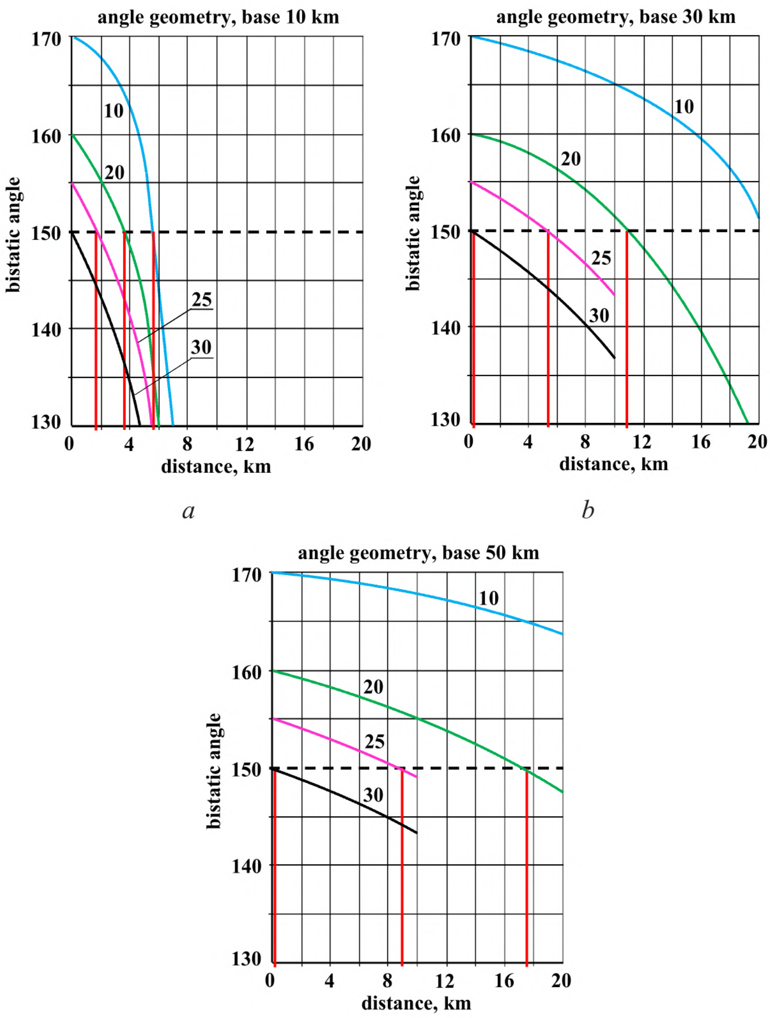


Fig. 6. To the calculation of the bistatic angle: *O* – a point of receiver standing; *A* – a point of transmitter standing; *B* – current position of the object; *OB* – variable (1st side); *OA* – 2nd side (base line); γ – internal angle (azimuth); β – bistatic angle (angle of base visibility)

An analysis of the course of the curves allows to conclude that an accepTable value of the observation sector of 50° is twice the deviation angle γ=25°. If now superimpose this sector on the base line in **Fig. 7**, it turns out that in both receiving positions, the approach paths are fully controlled. Let's note that the 60° sector is realized at a distance of up to 100 m.



a *b* *c*

Fig. 7. The values of bistatic angles (vertical axis, degrees) depending on the object's removal from the receiver (horizontal axis, kilometers) and the angle of deviation from the base line (curve parameter, degrees): *a* – base 10 km; *b* – base 30 km; *c* – base 50 km, the scale in range is the same

In **Fig. 7**, the dashed line corresponds to the specified minimum value of the bistatic angle of 150°. Red vertical lines indicate the estimated (geometric) observation of the object.

Finally, to determine σ_b at $\beta \neq 180°$ in formula (1), let's turn to the Cartesian coordinates and obtain:

$$\sigma_b(\cos\Theta_x, \cos\Theta_y) = \frac{4\pi}{\lambda^2}\left|\iint_{A_t} \exp j\frac{2\pi}{\lambda}(x\cdot\cos\Theta_x + y\cdot\cos\Theta_y)\mathrm{d}x\mathrm{d}y\right|^2, \tag{8}$$

where x, y – the ρ projections on the X, Y axis in the plane of the aperture A_t; $\cos\theta_x$, $\cos\theta_y$ – direction cosines of the ort r with respect to the same axes. It is assumed that the positive direction of the wave incident on the target coincides with the Z axis.

If the receiving position is located in the XZ or YZ plane, then in (8) either $\cos\theta_y=0$ or $\cos\theta_x=0$and $\theta_x=\beta-\pi/2$, so $\cos\theta_y=\sin\beta$. Then the bistatic EDZ of the object can be calculated as follows:

$$\sigma_b(\beta)=\frac{4\pi}{\lambda^2}\left|\int\limits_{x_{\min}}^{x_{\max}}\exp\left[j\frac{2\pi}{\lambda}x\cdot\sin\beta\right]\left[y_1(x)-y_2(x)\right]\mathrm{d}x\right|^2, \quad (9)$$

where $x_{\min,\, x\max}$ – side borders on the left and on the right; y_1, y_2 – vertical upper and lower boundaries of the aperture A_t.

The signal-to-noise ratio at the input of the receiving position for bistatic RLSs is calculated as:

$$q=\sqrt{\frac{P_i\tau_i G_0 G_t\sigma_b\lambda^2\eta}{(4\pi)^3 kT_{ef}\left|R_r-L\right|\left|R_{tr}-L\right|}}, \quad (10)$$

where P_i, τ_i – impulse power and pulse duration of the transmitting position; $G_{0,\,Gt}$ – the gains of the receiving and transmitting antennas; η – the total energy loss coefficient (η<1); k – Boltzmann constant; T_{eff} – effective noise temperature at the receiver input; R_r, R_{tr} – distance from the target to the receiving and transmitting positions; L – radius vector, which determines the location of the target.

To illustrate the increase in the signal-to-noise ratio from the bistatic angle, let's use the data from [20], which shows the signal-to-noise ratio versus the bistatic angle for the model of the Su-33 aircraft. The numerical data in the calculation of (10) used the technical characteristics of the radar "Casta-2" (made in Russia) [21]. Bistatic angle varies from 100° to 180°. The original graphs fluctuate quickly, so the figures show the envelopes of the signal-to-noise ratio. An analysis of the course of the curves in the graphs (**Fig. 8**) shows that in the range of 150°…180°, signal/noise 30...35 dB is provided (border – red line).

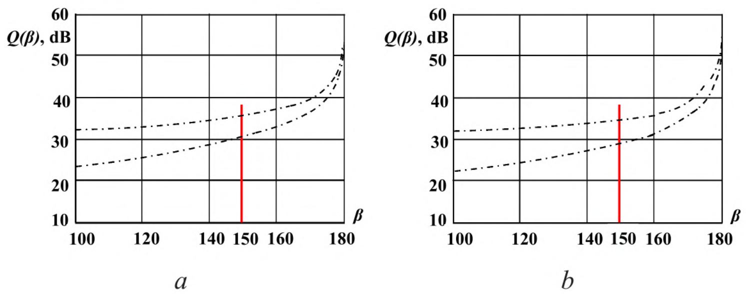


Fig. 8. The calculated dependences of the signal-to-noise ratio on the bistatic angle for the fighter model during scattering: *a* – forward "in full face"; *b* – forward "in profile"

Similar results were obtained by foreign researchers [14, 22].

6. Discussion of research results of covert observation of biological objects by means of bistatic RLS

Existing radar reconnaissance surface and surface objects are used, as a rule, for observation of land and water sections of the state border. Such devices can also be used to protect important military and economic objects (nuclear power plants, warehouses, consulates, etc.). The results of their work practically do not depend on weather conditions and the lack of optical visibility.

Earlier studies [11, 17] show that, in the approximation of physical optics, the shadow field of an object does not depend on the shape of the surface. The shadow field of the target is also not affected by the material of its surface (for example, plastic), or the radio-absorbing coatings, which drastically weaken the own diffuse field for the one-position variant.

The submissions indicate that the use of digital television transmitters to create a secretive bistatic system is quite possible – at least in a geometric interpretation in open areas. A wide network of television transmitters allows to choose from them the necessary warning to create a zone of intrusion into the protected area.

At the same time, it is possible to focus on using the reception sector of a single channel 50 degrees wide, which will ensure control of the territory at a distance of 1.5...5 km, depending on the size of the base. Full coverage of the frontal zone will require 4 receiving channels.

In addition, with low economic costs, it is possible to obtain a significant economic effect by significantly simplifying the multi-position and transition to bistatic RLS. The latter, with a certain configuration regarding the location object, allows observing objects that were not previously detected, which is confirmed by other works [23, 24].

At the same time, the well-known classical radiolocation formula requires clarification with reference to a change in the value of the bistatic angle depending on the changing location of the object in the geometric field of the system. Depending on the type and location of the radiation source, the geometry of the system varies significantly, which requires additional research. This is especially true of cosmic illumination from transponder satellites, and the main component will be played by the energy component, since there are no limitations on illumination in the area of the object.

The possibilities of the method are also limited in urban conditions, since it is not possible to distinguish the offender from the ordinary passer-by. In addition, the possibilities of organizing a circular area of responsibility, when the receiving device is located, for example, in the center of the protected object, have not been studied.

The application of the method for locating moving targets is considered, but the lower limit of the speed of movement is not defined, which requires further research on the possibility of distinguishing the signals reflected from violators and from the leaf cover of trees. Finally, it is possible to consider the possibilities of the method for detecting low-flying unmanned aerial vehicles for various purposes.

In the future, it is advisable to continue research on the use of methods of bistatic RLS (including secretive) with other illumination transmitters for solving problems of monitoring biological objects.

7. Conclusions

The found dependences of the signal-to-noise ratio $q(\beta)$ on the bistatic angle β allow to conclude that objects, including biological, are more reliable in the “forward-scattering” radar compared to the classical single-position, but in a smaller angular sector.

The use of digital radio and television broadcasting signals allows to focus on the size of the reception sector of a single channel 50 degrees wide, which will provide control over an area of 2...25 km^2 depending on the size of the base. Full coverage of the frontal zone will require 4 receiving channels.

If the geometry of the location of the position of the bistatic RLS and the object is such that during its movement the condition $\beta \approx 180°$ is met, then it is possible to use the effect of increasing the ERS to observe objects. It is possible to save the energy potential of the radar.

On the whole, the article is of a staging nature, and the analysis performed indicates that it is expedient to use the “forward-scattering” radar method to detect ground (surface) moving objects, including biological ones.

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SPECIAL MECHANISM OF CONDUCTION TYPE INVERSION IN PLASTICALLY DEFORMED *n*-Si

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Abstract

The aim of research is studying the mechanism of *n–p* inversion of the conduction type of deformed silicon crystals in the course of their thermal treatment. Initially, almost non-dislocation zone-melted phosphorus-doped n-Si single crystals with electron concentration of $2{\cdot}10^{14}$ cm^{-3} were studied. Uniaxial compression at temperature of 700 °C and pressure of 25 MPa increased the dislocation density to 10^{8} cm^{-2}. After long (within 30 min) cooling of the deformed crystals to room temperature, an *n–p* inversion of the conduction type occurred. The effect is explained by the formation of phosphorus–divacancy complexes PV_2 in the defective atmosphere of dislocations, which are acceptor centers with energy level of E_v+0.34 eV. The found out n–p inversion mechanism differs from the standard one for plastically deformed n-type semiconductors with a diamond-like crystalline structure, which consists in the formation of acceptor centers along edge dislocations.

Keywords: conduction type inversion, plastic deformation, thermal treatment, silicon.

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1. Introduction

Inversion of the type of conduction in semiconductors is an interesting physical effect, which has practical applications in solid-state electronics.

Usually, inversions to n-type are achieved by introducing acceptor impurities into the crystal and vice versa – by introducing donor atoms into the material with *p*-type conduction. An alternative direction to the chemical doping is the use of structural defects to influence the electrical properties of semiconductors. This approach, for its part, splits into the introducing (by irradiation, implantation, plasma treatment, annealing) of point and (by plastic deformation) extended defects of the crystal structure.

Briefly, the mechanism of the conduction type inversion induced by point defects can be described by the example of metal chalcogenides.

In the surface layer of *p*-type $Cd_xHg_{1-x}Te$ samples (x=0.22–0.25), when they were processed in hydrogen and/or argon plasma, an inversion of n-type conductivity was observed [1]. Despite the chemical activity of hydrogen, such inversion seems to be a purely radiation effect: excess mercury accumulated in micro-inclusions on the surface diffuses deep into the crystal and there suppresses defects of acceptor nature.

In the n-type $Cd_xHg_{1-x}Te$ samples (x=0.19–0.32), after implantation of ions of elements I, III, and VIII groups and diffusion thermal annealing in atmosphere of saturated mercury vapor, an inversion to the p-type occurred [2]. The study of the recombination characteristics of such crystals has shown that, regardless of the electrical activity/neutrality of the implanted impurity their annealing leads to the formation of radiation defects of common nature. They should be vacancy complexes of the $V_{Hg}V_{Te}$ type in neutral state. The local levels in the band gap, through which carrier current recombines, are associated with same centers.

Inversion processes of the conduction type were also investigated [3] in the epitaxial films of the *p*-$Pb_{0.8}Sn_{0.2}Te$ solid solution under the action of laser radiation. It is also concluded that stable n-type inversion states arise due to the formation of bivacancies of metal and chalcogen.

Inversion of conduction from n- to p-type in zinc selenide samples doped with indium ZnSe:In was detected [4] during their annealing in atmosphere of saturated selenium vapor. The phenomenon was associated with the amphoteric nature of indium as dopant. In the process of annealing, a part of In atoms localized in the zinc sublattice goes out into the crystal lattice interstitials. Their association leads to the formation of micro-defects in the form of indium inclusions. These micro-defects serve as sources of effective diffusion of indium in selenium vacant sites, where they act as acceptors.

A generalized explanation of the inversion of the conduction type of metal chalcogenides is the following. These crystals are characterized, on the one hand, by high concentrations of electrically active vacancies of both metals and chalcogen, and, on the other hand, by metal-rich micro-inclusions. Stimulated by external influence (annealing, laser irradiation, ion implantation, etc.) processes of disintegration of micro-inclusions and diffusion of released atoms (especially under conditions of excessive pressure of metal vapor) can lead to change in the type of conduction from hole to electronic, since metal atoms when are filling vacancies in the chalcogen sublattice eliminate two free holes from each vacancy. At the same time, metal ions in interstitials are singly charged donors and for this reason the same processes occurred in neutral defective atmosphere can lead to the opposite direction of inversion.

In most cases, the associated with point defects conduction type inversion occurs when the concentration of donors n_d equals the concentration of acceptors n_a: $n_d=n_a$. And in the concentration region with center at $n_d \approx n_a$, Fermi level step of width $\sim kT/E_g$ is observed. Here k is the Boltzmann constant, T is the sample temperature, and E_g is the band gap of the semiconductor. However, the condition $n_d=n_a$ is not always met. For example, in semi-insulating *p*-CdTe single crystals, the conduction type inversion was detected [5] at compensation degrees significantly lower than 1. This and other features of the measured temperature-dependences of the electrical characteristics are explained by the special compensating mechanism in the semi-insulating material – in this case, by the presence of acceptor levels located above the middle of the band gap.

As for the inversion of the type of conduction associated with the introducing of extended defects into a semiconductor crystal, it has been studied in most detail for diamond-like structures. Unsaturated chemical bonds in the core of partial dislocations with an edge component in such a structure form acceptor centers with a system of electronic energy levels inside the band gap. Thus, high concentration of dislocations in diamond-like semiconductors always leads to the hole-type conduction.

Single-crystalline diamond, as is known, is an insulator, not a semiconductor. Since plastic deformation implies the appearance of both possible types of dislocations, significant plastic deformation of insulating diamonds results [6] in semiconductor diamonds, all of which without any exception have only the hole-type conduction.

As a criterion for the onset of the inversion of the conduction type associated with the introducing of dislocations into a semiconductor sample, the condition was proposed that differs from the one given above for the case when the inversion is caused by the introducing of point defects. Having in view diamond-like crystals, it is possible to formulate inversion criterion for *n*-type semiconductors in which dislocations with acceptor properties are introduced. Now the role of the concentration of acceptor centers is played by the ratio $n_{aD}=N_D/a$, where N_D is the dislocations density and a is the interatomic distance in the crystal. If the capacitance of the dislocation level closest to the valence band edge is sufficiently small, then with an increase in the density of dislocations such a value (again not necessarily equal to 1) of the ratio n_{aD}/n_d is reached, which corresponds to a diffusive step at the Fermi level indicating the n–p inversion of the conduction type.

For elementary semiconductors like germanium Ge and silicon Si, which crystallize in diamond-like structure, the two-level phenomenological model was proposed [7]. In particular, in *n*-Si, a dislocation with an edge component must be charged and possess two acceptor levels, respectively, at distances $E_1 \approx 0.42$ and $E_2 \approx 0.67$ eV from the valence band edge. The capacity of the deeper level is always close to 1, $C_2 \approx 1$, and the capacity C_1 of another level may vary. If C_1 is sufficiently small ($C_1 \sim 0.01$), then with an increase in the density of dislocations at the Fermi level the step is formed with height of order of the difference E_2-E_1. This behavior is considered to be a sign of conduction type inversion.

The aim of this research is studying the mechanism of *n–p* inversion of plastically deformed *n*-Si crystals during their thermal treatment; consideration of the possibility of interpreting this effect on the basis of the spectrum of complex point defects characteristic of the real structure of silicon.

2. Experimental part

Initially, obtained by zone-melting almost non-dislocation single crystals of n-Si doped with phosphorus of concentration of 2×10^{14} cm^{-3} and with background oxygen content of 2×10^{16} cm^{-3} have been studied.

Plastic deformation led to the dislocation multiplication with density up to ~10^8 cm^{-2}. This value was determined by etching pits with the error of $\pm5\times10^6$ cm^{-2}. The deformation was performed by uniaxial compression acting in the main slip plane at temperature of 700 °C and pressure of 25 MPa.

After deformation, the samples were cooled slowly (30 min) together with the furnace or rapidly (30 s), for which they abruptly dropped into glycol.

The carrier concentration N was measured by the Hall method in the magnetic field of strength 10 kOe in the temperature T range from nitrogen boiling point to room temperature: 77–300 K. Note that in the figure given in the next section, the experimental points for the low-temperature part of this range are not shown. The point is that, for low-conducting samples these measurements are impossible, and for highly-conducting ones the experimental values of the charge carriers' concentration are almost indistinguishable from each other. The Hall factor was assumed to be 1.

The electronic energy levels of defects were determined from the slope of the dependences $\lg N – 10^3/T$.

3. Results

The temperature-dependence of the electrons concentration (**Fig. 1**) for the initial sample in the entire measurement interval corresponds to the depletion of phosphorus dopant atoms by electrons: N=const≈2×10^{14} cm^{-3} (Curve 1).

After plastic deformation with cooling for 30 min, n-type samples with N_D~10^8 cm^{-2} turned into p-type. The holes concentration in the valence band was determined by the ionization of centers with energy of E_v+0.34 eV (Curve 2).

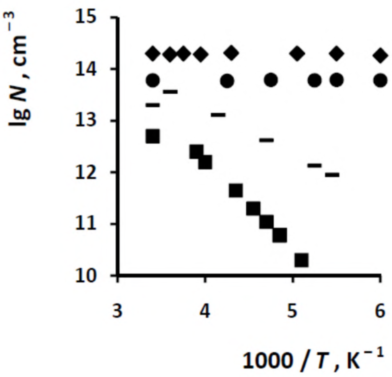

Fig. 1. Temperature-dependence of charge free carriers concentrations in plastically deformed silicon: 1 – before deformation (♦); after deformation at 700 °C and 2 – cooling for 30 min (■), 3 – annealing for 1 min at 700 °C and rapid cooling in glycol (–), and 4 – annealing at 700 °C for ≥35 min (●)

All possible non-equilibrium defects in n-Si crystals, which can be formed by vacancies and impurity atoms during their plastic deformation and cooling, are stable up to 600 °C. Therefore, by heating to 700 °C it is possible to ensure their complete dissociation. As for the equilibrium concentration of intrinsic point defects in silicon crystals at 700 °C, it is about 10^{14} cm^{-3}.

If both the equilibrium and released after 1 min annealing vacancies are fixed in nonequilibrium state by rapid cooling, the crystal again becomes of n-type and the electron concentration is determined by ionization of centers with energy E_c–0.18 eV, which corresponds to A-centers, i. e. complexes of oxygen with vacancy OV (Curve 3).

After prolonged (for ≥35 min) annealing at 700 °C, the concentration of electrons in the conduction band is again determined by the shallow donors (Curve 4).

4. Discussion

Before discussing our results on the inversion of the type of conduction in n-Si, it is advisable to present the results of the work [8], in which the same effect was studied in highly pure material irradiated with γ-quanta. In the process of irradiating the samples, the electron concentration was first reduced to its intrinsic value, and then inversion of conduction into the p-type together with corresponding increase in the holes concentration occurred. The Fermi level as a result of γ-irradiation in highly pure silicon tends to the position at E_v+0.39 eV in the band gap. The following important conclusion from this result is that the inversion of the conduction type in n-Si is not necessarily associated with dislocation acceptors, but may be due to point defects.

Similarly, the role of plastically deformed dislocations introduced into our samples does not seem to be decisive. This conclusion is supported by the possibility of n-type conduction recovery by thermal treatment, in which dislocations are not annealed. In the samples tested by us, the effective concentration of dislocation acceptors is insufficient for *n–p* inversion. This value can be easily estimated from the difference in the electron concentrations in initial, i. e. not deformed, and deformed and continuously annealed samples (Curves 1 and 4): 1.4×10^{14} cm^{-3}.

In addition to the above, when interpreting the results obtained it is necessary to take into account that, during plastic deformation in silicon crystals along with each dislocation the ambient atmosphere of point defects are formed, in which the concentration of vacancies that actively interact with impurity atoms is particularly high [9].

When cooling plastically deformed samples for 30 min in the initial stages of the process (up to 300 °C), it seems that only A-centers, i. e. complexes *OV*, are formed. It is assumed that further on the basis of the A-centers there are formed deep complex defects also containing oxygen atoms and vacancies, for example, OV_n and O_nV (n=1, 2, 3) with ionization energies ≥0.44 eV, which are characterized by high thermal stability (with annealing temperature ≥350 °C) [10].

In the temperature region around 250 °C, divacancies (E_c–0.39 eV) and defects with energy level E_c–0.54 eV are predominantly formed. The temperature ranges of annealing of these two defects almost coincide: 250–350 °C [11]. When the annealing temperature is ≤150 °C, defects with low thermal stability can be formed in the crystal, for example, E-centers – complexes of doping phosphorus atoms with vacancies *PV*. They are deep acceptors and electrically neutral at this temperature. Presumably, in the same temperature range, in the neutral charge state there are monovacancies, which correspond to the energy level E_c–0.28 eV [12].

By blocking the phosphorus atoms, each *E*-center from the conduction band captures only one electron [13]. At an annealing temperature ≤150 °C, specifically in the region of 100 °C, negatively charged acceptor centers PV_2^- can be formed with the capture of an additional electron (by the reaction $2E+V\rightarrow PV_2^-+P^+$), which corresponds to the energy level E_v+0.34 eV and are annealed in the temperature range of 400–500 °C [14]. It seems that, the ionization of just these centers determines the change in the holes concentration in the valence band, which leads to *n–p* inversion of the conduction type during the thermal treatment of plastically deformed *n*-Si samples.

The PV_2 complexes are formed at the end of the crystal cooling process when all possible deep acceptor centers have been already formed (*E*-centers, divacancies, V_nO- or O_nV-type complexes, defect of unknown nature with the level of E_c–0.54 eV, etc.).

At the time of the formation of the PV_2 complexes, all the electrons from the conduction band are already captured by the deep centers listed above. In order for these electrons to go to the level of E_v+0.34 eV, they must first free themselves, i. e. go to the conduction band, what is possible at temperature of ~350 K. Correspondingly, the PV_2 complexes cannot capture electrons from the conduction band at relatively low temperatures (~300 K).

The transition of electrons from the valence band to the level at E_v+0.34 eV begins in the region of 200 K. It leads to n–p inversion of the conduction type of the studied samples (Curve 2). And the holes concentration in inverted samples in the range 77–300 K is determined by the concentration of E-centers converted into PV_2 complexes.

5. Conclusion

Thus, in n-type single crystalline plastically deformed at 700 °C and slowly cooled to room temperature, the *n–p* inversion occurs. The observed effect is explained by the formation of phosphorous-divacancy complexes PV_2 with an acceptor energy level E_v+0.34 eV in defective atmosphere of dislocations multiplied by plastic deformation. This is a special mechanism for the inversion of the conduction type in plastically deformed silicon, which is different from the standard one associated with dislocation acceptors.

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TRANSPORTATION MANAGEMENT IN A DISTRIBUTED LOGISTIC CONSUMPTION SYSTEM UNDER UNCERTAINTY CONDITIONS

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Abstract

The problem of supply management in the supplier-to-consumer logistics transport system has been formed and solved. The novelty of the formulation of the problem consists in the integrated accounting of costs in the logistic system, which takes into account at the same time the cost of transporting products from suppliers to consumers, as well as the costs for each of the consumers to store the unsold product and losses due to possible shortages. The resulting optimization problem is no longer a standard linear programming problem. In addition, the work assumes that the solution of the problem should be sought taking into account the fact that the initial data of the problem are not deterministic. The analysis of traditional methods of describing the uncertainty of the source data. It is concluded that, given the rapidly changing conditions for the implementation of the delivery process in a distributed supplier-to-consumer system, it is advisable to move from a theoretical probability representation of the source data to their description in terms of fuzzy mathematics. At the same time, in particular, the fuzzy values of the demand for the delivered product for each consumer are determined by their membership functions.

Distribution of supplies in the system is described by solving a mathematical programming problem with a nonlinear objective function and a set of linear constraints of the transport type. In forming the criterion, a technology is used to transform the membership functions of fuzzy parameters of the problem to its theoretical probabilistic counterparts – density distribution of demand values. The task is reduced to finding for each consumer the value of the ordered product, minimizing the average total cost of storing the unrealized product and losses from the deficit. The initial problem is reduced to solving a set of integral equations solved, in general, numerically. It is shown that in particular, important for practice, particular cases, this solution is achieved analytically.

The paper states the insufficient adequacy of the traditionally used mathematical models for describing fuzzy parameters of the problem, in particular, the demand. Statistical processing of real data on demand shows that the parameters of the membership functions of the corresponding fuzzy numbers are themselves fuzzy numbers. Acceptable mathematical models of the corresponding fuzzy numbers are formulated in terms of bifuzzy mathematics. The relations describing the membership functions of the bifuzzy numbers are given. A formula is obtained for calculating the total losses to storage and from the deficit, taking into account the bifuzzy of demand. In this case, the initial task is reduced to finding the distribution of supplies, at which the maximum value of the total losses does not exceed the permissible value.

Keywords: production-consumption logistic system, transportation problem, fuzzy and bifuzzy demand, optimization of fuzzy criteria.

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1. Introduction

The canonical transport problem of linear programming is formulated as follows [1–4].

Let there be m points of production of a certain product and n points of its consumption. Production and consumption are balanced, i. e. total production and consumption are equal. The task is in finding a rational transportation plan from production points to consumption points, at which transport costs are minimal. The resulting transportation plan must meet the following requirements:

1) demand of each of the points of consumption must be fully met;

2) all the product produced at each production point must be used.

Let's formalize the task. Let's introduce the following notation:

x_{ij} – the number of units of the product transported from the *i*-th point of production to the *j*-th point of consumption;

c_{ij} – the cost of transporting a unit of product from the *i*-th point to the *j*-th;

a_i – the number of units of product produced in the *i*-th point;

b_j – the number of units of product consumed in *j*-th point.

In the accepted notation, the problem is reduced to finding a set of variables $\{x_{ij}\},\ i=1,2,...,n,$ minimizing the objective function

$$L(\{x_{ij}\})=\sum_{i=1}^{m}\sum_{j=1}^{n}c_{ij}x_{ij} \tag{1}$$

and satisfying the constraints

$$\sum_{i=1}^{m}x_{ij}=b_j,\quad j=1,2,...,n; \tag{2}$$

$$\sum_{j=1}^{n}x_{ij}=a_i,\quad i=1,2,...,m; \tag{3}$$

$$x_{ij}\geq 0,\quad i=1,2,...,m;\quad j=1,2,...,n.$$

In the system of the assumptions made here, the most rigid and almost always broken is the assumption that the magnitude of the demand at each of the consumption points is precisely known. In this regard, it is much more natural to assume that there is uncertainty about the values $b_j,\ j=1,2,...,n.$ Its character may be different. If for each point of consumption a preliminary sampling of the demand values is obtained, then its standard statistical processing within the framework of the theoretical probabilistic approach allows to obtain the distribution density of the observed quantity of demand and its moments. In practice, this is not the case: the available data are sufficient only to obtain satisfactory estimates of the range of possible values of demand at each point and its mathematical expectation. This circumstance leads to the expediency of using a fuzzy mathematics apparatus to describe the transportation system [5–9]. Let's formulate the formulation and solve the transportation problem under conditions when the demand at the points of consumption is not clearly defined [10].

2. Mathematical model of transportation management under fuzzy demand

Taking this into account, let's introduce a description of the possible demand values at the points of consumption b_j by membership functions $\phi_j(b_j),\ j=1,2,...,n.$ Some freedom that emerges in this case when selecting the order quantity of a product z_j has an important advantage, since it allows to take into account differences in the amount of losses in case of an unsuccessful selection of the order value. Let's introduce:

$R_1(z_j)$ – the magnitude of the losses occurring in cases where the order z_j exceeds the demand and there is a need to store unsold product;

$R_2(z_j)$ – the magnitude of the losses that occur if the demand b_j at a particular j-th sales point of the product exceeds the order z_j and as a result there are losses from the shortage.

It is clear that in this situation the set of values z_j, $j=1,2,...,n$, must be chosen in some reasonable way. In this regard, the initial formal formulation of the problem is converted to the following: find sets $Z=(z_j)$ and $X(Z)=\{x_{ij}((z_j)\}$, and minimizing

$$L(x_{ij}(z_j))=\sum_{j=1}^{n}R_1(z_j)+\sum_{j=1}^{n}R_2(z_j)+\sum_{i=1}^{m}\sum_{j=1}^{n}c_{ij}x_{ij}(z_j) \tag{4}$$

and satisfying the constraints

$$\sum_{j=1}^{n}x_{ij}(z_j)=a_i,\ \ i=1,2,...,m, \tag{5}$$

$$\sum_{i=1}^{m}x_{ij}(z_j)=z_j,\ \ j=1,2,...,n, \tag{6}$$

$$\sum_{j=1}^{n}z_j=\sum_{i=1}^{m}a_i, \tag{7}$$

$$x_{ij}(z_j)\geq 0,\ \ i=1,2,...,m,\ \ j=1,2,...,n. \tag{8}$$

Let's obtain an analytic description of the functions, $R_1(z_j)$ and $R_2(z_j)$, $j=1,2,...,n$. Since z_j – fuzzy numbers, then any of their functions is also a fuzzy number. Using membership functions $\phi_j(b_j)$, let's introduce functions

$$\tilde{\phi}_j(b_j)=\frac{\phi_j(b_j)}{\int_{G_j}\phi(b_j)db_j},\ \ j=1,2,...,n, \tag{9}$$

where G_j – the range of possible values

The obtained functions $\tilde{\phi}_j(b_j)$ have all the properties of the density distribution of random variables: they are non-negative and satisfy the normalization condition, that is,

$$\int_{G_j}\tilde{\phi}(b_j)db_j=1,\ \ j=1,2,...,n. \tag{10}$$

Then the function $\phi_j(b_j)$ can be used to calculate the expected value of a fuzzy number z_j.

$$m_j=\int_{G_j}b_j\tilde{\phi}(b_j)db_j,\ \ j=1,2,...,n, \tag{11}$$

which is a natural analogue of the expectation value of a random variable defined in probability theory using its density.

In this case, the expected value of the cost of storing the unrealized part of the product will be equal to

$$R_1(z_j)=\alpha_j\int_{0}^{z_j}(z_j-b_j)\tilde{\phi}(b_j)db_j, \tag{12}$$

where α_j – the average cost of storing a unit of product in j-th sales point, $j=1,2,...,n.$

Similarly, let's define the average losses from the deficit

$$R_2(z_j)=\beta_j\int_{z_j}^{\infty}(b_j-z_j)\tilde{\phi}(b_j)db_j, \tag{13}$$

where β_j – the average profit derived from the sale of a unit of product in the j-th sales point, $j = 1,2,...,n.$

The obtained relations (12) and (13) can be used to independently calculate rational values z_j for each of the sales points, minimizing the total storage costs of the unsold part of the product and the loss from the deficit in this particular item. To this end, for the j-th sales point let's introduce

$$R_j(z_j) = R_1(z_j) + R_2(z_j) = \alpha_j \int_0^{z_j} (z_j - b_j)\tilde{\phi}_j(b_j)db_j + \beta_j \int_{z_j}^{\infty} (b_j - z_j)\tilde{\phi}_j(b_j)db_j =$$

$$\alpha_j z_j \int_0^{z_j} \tilde{\phi}_j(b_j)db_j - \alpha_j \int_0^{z_j} b_j\tilde{\phi}_j(b_j)db_j + \beta_j \int_{z_j}^{\infty} b_j\tilde{\phi}_j(b_j)db_j - \beta_j z_j \int_{z_j}^{\infty} \tilde{\phi}_j(b_j)db_j,$$

$$j = 1,2,...,n.$$

Now let's find a rational value z_j by differentiating $R_j(z_j)$ in z_j, equating its result to zero and solving this equation. Because

$$\frac{d}{dz_j}\int_0^{z_j} \tilde{\phi}_j(b_j)db_j = \tilde{\phi}_j(z_j), \quad \frac{d}{dz_j}\int_{z_j}^{\infty} \tilde{\phi}_j(b_j)db_j = -\tilde{\phi}_j(z_j),$$

$$\frac{d}{dz_j}\int_0^{z_j} b_j\tilde{\phi}_j(b_j)db_j = z_j\tilde{\phi}_j(z_j), \quad \frac{d}{dz_j}\int_{z_j}^{\infty} b_j\tilde{\phi}_j(b_j)db_j = -z_j\tilde{\phi}_j(z_j),$$

then

$$\frac{dR_j(z_j)}{dz_j} = \alpha_j \int_0^{z_j} \tilde{\phi}_j(b_j)db_j + \alpha_j z_j\tilde{\phi}_j(z_j) - \alpha_j z_j\tilde{\phi}_j(z_j) - \beta_j z_j\tilde{\phi}_j(z_j) - \beta_j \int_{z_j}^{\infty} \tilde{\phi}_j(b_j)db_j + b_j z_j\tilde{\phi}_j(z_j) =$$

$$\alpha_j \int_0^{z_j} \tilde{\phi}_j(b_j)db_j - \beta_j(1 - \int_0^{z_j} \tilde{\phi}_j(b_j)db_j) = (\alpha_j + \beta_j)\int_0^{z_j} \tilde{\phi}_j(b_j)db_j - \beta_j = 0.$$

Hereof

$$\int_0^{z_j} \tilde{\phi}_j(b_j)db_j) = \frac{\beta_j}{\alpha_j + \beta_j}. \tag{14}$$

The resulting equation is solved numerically with respect to z_j, and if the function $\tilde{\phi}_j(b_j)$ is integrable, then analytically. Let, for example, the distribution density $\tilde{\phi}_j(b_j)$ corresponds to the Rayleigh law, that is,

$$\tilde{\phi}_j(b_j) = \frac{b_j}{\sigma^2}\exp\left\{-\frac{b_j^2}{2\sigma^2}\right\}.$$

In this case, the equation with respect to z_j

$$1 - \exp\left\{-\frac{z_j^2}{2\sigma^2}\right\} = \frac{\beta_j}{\alpha_j + \beta_j},$$

from which

$$\exp\left\{-\frac{z_j^2}{2\sigma^2}\right\} = 1 - \frac{\beta_j}{\alpha_j + \beta_j} = \frac{\alpha_j}{\alpha_j + \beta_j}, \quad z_j = \pm\sigma\sqrt{2}\ln\frac{\alpha_j + \beta_j}{\alpha_j}.$$

Choosing a positive root

$$z_j^{(0)} = \sigma\sqrt{2\ln\frac{\alpha_j + \beta_j}{\alpha_j}}, \quad j = 1, 2, ..., n.$$

The considered task becomes significantly more difficult if the parameters of the membership function of a fuzzy demand value are not clearly defined. Let's suppose that this demand x is given by a triangular fuzzy number with the membership function (15)

$$\mu_x(x) = \begin{cases} 0, & x < a, \\ \dfrac{x-a}{c-a}, & a \le x < c, \\ \dfrac{b-x}{b-c}, & c \le x \le b, \\ 0, & x > b. \end{cases} \tag{15}$$

Let's suppose further, in the practical determination of the parameters (a, b, c) of the corresponding membership function, it turns out that these parameters can't be defined precisely. If fuzzy numbers are used to describe these parameters, the original number x turns out to be bifuzzy. Such fuzzy numbers are introduced in [11], but the formal technologies for performing operations on them are not defined. In connection with this, let's consider the problem of describing the membership function of a bifuzzy number [12].

Let, for example, the membership function of a fuzzy number x has the form (15). Suppose now that the parameters of this membership function are fuzzy numbers. Let's assume, for simplicity, that, in particular, the parameter a of the membership function $\mu_x(x)$ is a triangular fuzzy number with the membership function $\mu_a(a)$ having the form

$$\mu_a(a) = \begin{cases} 0, & a < a_1, \\ \dfrac{a-a_1}{c_1-a_1}, & a_1 \le a < c_1, \\ \dfrac{b_1-a}{b_1-c_1}, & c_1 \le a \le b_1, \\ 0, & a > b_1. \end{cases} \tag{16}$$

Let's consider the situation. A fuzzy number x with the membership function (15) corresponds to the degree of belonging to the universe $X = [a, b]$, equal to (if $a \le x < c$) a crisp number $\frac{x-a}{c-a}$. If now a is a fuzzy number, then this degree of membership also becomes a fuzzy number, because with fuzzy a a variety of membership functions $\mu(x, a)$ arise, each of which for a fixed number x sets the degree of number x membership to the new universe $X = [a_1, b]$.

Let's find the membership function of a fuzzy number $u = (x-a)/)(c-a)$, which determines the degree of belonging of the bifuzzy number x to the universe $X = [a_1, b]$, taking into account the parameter a ambiguity.

Using standard technology [5–9] and rules for performing operations on fuzzy numbers:

$$u = f(a) = \frac{x-a}{c-a},$$

$$a = f^{-1}(u) = \frac{uc-x}{u-1}.$$

In this case

$$u \in \left[\frac{x-a_{\max}}{c-a_{\max}}, \frac{x-a_{\min}}{c-a_{\min}} \right].$$

Then $\mu(u) = \mu_a(u)$.

The analytical expression for $\mu_a(u)$ depends on the choice of value x.

Let $x > b_1$. Then $a \in [a_1, b_1]$.

At the same time let's obtain

$$\mu_a(u) = \begin{cases} 0, & u < \dfrac{x-b_1}{c-b_1}, \\ \dfrac{u(c-b_1)-(x-b_1)}{(b_1-c_1)-u(b_1-c_1)}, & \dfrac{x-b_1}{c-b_1} \le u \le \dfrac{x-c_1}{c-c_1}, \\ \dfrac{(x-a_1)-u(c-a_1)}{(c_1-a_1)-u(c_1-a_1)}, & \dfrac{x-c_1}{c-c_1} < u \le \dfrac{x-a_1}{c-a_1}, \\ 0, & u > \dfrac{x-a_1}{c-a_1}. \end{cases} \tag{17}$$

Now let $c_1 \le x \le b_1$. Then

$$\mu_a(u) = \begin{cases} 0, & u < 0, \\ \dfrac{u(c-x)}{(x-c_1)-u(x-c_1)}, & 0 \le u \le \dfrac{x-c_1}{c-c_1}, \\ \dfrac{(x-a_1)-u(c-a_1)}{(c_1-a_1)-u(c_1-a_1)}, & \dfrac{x-c_1}{c-c_1} < u \le \dfrac{x-a_1}{c-a_1}, \\ 0, & u > \dfrac{x-a_1}{c-a_1}. \end{cases} \tag{18}$$

Finally if $a_1 < x < c_1$, then

$$\mu_a(u) = \begin{cases} 0, & u < 0, \\ \dfrac{(x-a_1)-u(c-a_1)}{(1-u)(x-a_1)}, & 0 < u < \dfrac{x-a_1}{c-a_1}, \\ 0, & u > \dfrac{x-a_1}{c-a_1}. \end{cases} \tag{19}$$

The technologies discussed above make it possible to obtain models of deep uncertainty in problems of logistics based on analytical descriptions of the membership function of fuzzy variables that reflect the state and dynamics of the behavior of real objects.

The obtained relation for bifuzzy demand allows to solve the following problem in terms of interval mathematics: to find the range of demand X, values for which the value and the membership function $\mu(u)$ will not be lower than the specified

$$x \in [x_{\min}(u), x_{\max}(u)].$$

The boundaries of the range are determined by the ratios

$$u=\frac{x_{\min}(u)-a_1}{c-a_1}=\frac{b-x_{\max}(u)}{b-c},$$

from which

$$x_{\min}(u)=a_1+u(c-a_1),\ \ x_{\max}(u)=b-u(b-c). \tag{20}$$

Then, for any particular order z value, the range of values for the unrealized balance can be determined.

$$r_{rem}\in[z-x_{\max}(u),z-x_{\min}(u)], \tag{21}$$

as well as the range of possible deficit

$$r_{def}\in[x_{\min}(u)-z,x_{\max}(u)-z]. \tag{22}$$

Corresponding storage costs and losses from deficit are equal

$$R_1(z,u)=\alpha r_{rem},$$

$$R_2(z,u)=\beta r_{def}. \tag{23}$$

Substituting (20)–(22) into (23), let's obtain

$$R_1(z,u)\in\alpha[z-x_{\max}(u),z-x_{\min}(u)]=$$
$$\alpha[z-(b-u(b-c)),z-(a_1+u(c-a_1)];$$

$$R_2(z,u)\in\beta[x_{\min}(u)-z,x_{\max}(u)-z]=$$
$$\beta[a_1+u(c-a_1)-z,b-u(b-c)-z].$$

At the same time, the range of possible values of total losses for given (z,u) is determined by the ratio

$$R_\Sigma(z,u)\in[\alpha(z-x_{\max}(u))+\beta(x_{\min}(u)-z),\alpha(z-x_{\min}(u))+\beta(x_{\max}(u)-z,]=$$
$$=[\beta(x_{\min}(u)-\alpha x_{\max}(u)-z(\beta-\alpha),\beta x_{\max}(u)-\alpha x_{\min}(u)-z(\beta-\alpha)]. \tag{24}$$

Relation (24) allows to formulate the following interval problem of choosing a rational value of the volume of the ordered product: find z the maximum value of the total losses $R_\Sigma(z,u)$ that does not exceed the allowable value $R_\Sigma^0(z,u)$. The sought value $z^{(0)}$ is determined, taking into account (24) by solving the inequality:

$$\beta x_{\max}(u)-\alpha x_{\min}(u)-z(\beta-\alpha)\le R_\Sigma^0, \tag{25}$$

From which

$$z\ge\frac{\beta x_{\max}(u)-\alpha x_{\min}(u)}{\beta-\alpha}. \tag{26}$$

The modernization of the mathematical scheme for calculating the rational value of the ordered product, taking into account the bifuzzy of demand for each consumer, necessitates a corresponding modernization and criterion (4) of the initial supply management problem. At the same time, it is natural to reformulate this task as follows: find sets $z=(z_j)$ and $X(Z)=\{x_{ij}(z_j)\}$, minimizing

$$(x_{ij}(z_j))=\sum_{i=1}^{m}\sum_{j=1}^{n}c_{ij}x_{ij}(z_j)+\sum_{j=1}^{n}(z_j-z_j^{(0)})^2$$

and satisfying constraints (5)–(8).

The most simple and effective procedure for solving this problem is implemented by the Nelder-Mead method.

3. The results of the development of solutions to the management problem in a distributed consumption system

The paper deals with the problem of supply management in a distributed system "suppliers-consumers". The traditionally used procedure for solving this problem is a two-step process. At the first stage, for each consumer, taking into account the demand for the product being sold, the task of calculating the rational value of the ordered product is minimized, minimizing the cost of storing the unrealized balance and losses from a possible shortage. At the second stage, the usual transport problem of linear programming is solved taking into account the formed set of orders for the product delivered to the points of consumption. An alternative method for solving the original problem is proposed using a complex criterion that takes into account the cost of transporting and selling the delivered product. The implementation of this approach provides a tangible gain in the total cost of sales of the product produced in a single production-delivery-consumption logistic system. This gain grows as the volume of produced and sold product increases. The obvious advantages of the proposed approach are confirmed by calculating the efficiency of a simple model of the system under consideration, which contains two production points and five consumption points. At the same time, a matrix of average delivery costs of a unit of product for each pair "producer-consumer" and a vector of rational values of the ordered product are specified. The problem was solved using the traditional two-step procedure, and then the proposed method. The gain in the total cost of sales amounted to 8 %. With an increase in the total volume of the product sold twice the gain increased to 11.2 %.

4. Discussion of the results of solving the problem of transportation management in the logistic system under uncertainty conditions

A method is proposed for solving the problem of supply management in a production-delivery-consumption logistics system, taking into account the modification of the traditional theoretical probabilistic mathematical model for describing the uncertainty of the initial data. It is shown that a more adequate is a model that uses their binaries. The optimization problem arising from this is not solved by traditional methods. In the paper, the desired solution is obtained in terms of interval mathematics. The direction of further research: the development of exact methods for solving optimization problems, the parameters of which are not clearly defined [13, 14].

5. Conclusions

1. A method is developed for transportation management in a distributed production-delivery-consumption logistic system under conditions of high uncertainty in the source data, which is described bifuzzy.

2. Unparalleled technology for calculating membership functions for fuzzy numbers, the numerical parameters of which themselves are not clearly described, is developed.

3. A method is developed for solving a nontrivial optimization problem, the parameters of which are given bifuzzy. In the well-known literature, such problems were not considered. To solve the problem, an interval approach is proposed, which determines the approximate solution of the problem, which asymptotically approaches the exact solution.

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INVESTIGATION OF THE DYNAMIC LOADING OF A BODY OF PASSENGER CARS DURING TRANSPORTATION BY RAIL FERRY

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Abstract

To ensure the safety of passenger carriages by rail ferries, mathematical modeling of dynamic loading is performed. The accelerations are determined as components of the dynamic load acting on the body of a passenger car. This takes into account the actual hydrometeorological characteristics of the water area of the railway ferry. The calculations are made in relation to the railway ferry "Mukran", which moves the Baltic Sea. The model takes into account that the car body is rigidly fixed relative to the deck and during the oscillations of the railway ferry follows the trajectory of its movement. The solution of the mathematical model is implemented in the Mathcad software environment using the Runge-Kutta method. It is established that the maximum value of the acceleration acting on the car body is 1.8 m/s^2.

Determination of the dynamic loading of the passenger car body during transportation by sea is also carried out by computer simulation. The calculations were carried out in the CosmosWorks software package using the finite element method. Numerical values and acceleration distribution fields are obtained relative to the carriage body structure of a passenger car.

A modal analysis of the car body during transportation by rail ferry is carried out. The numerical values of the critical frequencies and waveforms are obtained.

To check the adequacy of the developed models, a calculation is made according to the Fisher criterion. It is established that the hypothesis of adequacy is not rejected.

The research will contribute to the creation of recommendations on the safety of passenger carriages by railway ferries, as well as the manufacture of their modern structures in terms of car-building enterprises.

Keywords: passenger car, dynamic loading, body acceleration, loading modeling, modal analysis, rail-ferry transportation.

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1. Introduction

Creating competition in the market of transport services leads to the commissioning of combined transport systems. In countries having access to marine waters, rail-ferry traffic has become widespread. The peculiarity of such transportation is the possibility of following the wagons by sea on special vessels – railway ferries. At present, transportation by sea is carried out not only freight, but also passenger cars (**Fig. 1**).

a *b*

Fig. 1. Transportation of passenger cars on rail ferries by sea:
a – "Annenkov" ferry (Sea of Azov); *b* – Fata Morgana ferry (Strait of Messina)

In order to ensure the stability of the car bodies in transit by sea, they are fixed relative to the decks. For this purpose, special multi-current funds are used. On the bodies of passenger cars of the last years of construction, special brackets are provided for interacting with fastening means (**Fig. 2**).

a *b*

Fig. 2. Staples for fixing the passenger car body relative to the deck: *a* – fastening to the car body; *b* – placement along the car

To ensure the safety of transportation of cars by sea, it is important to study their dynamic loading [1–3]. Analysis of the existing regulatory and technical documentation allows to conclude that the issue of dynamic loading of bodies of passenger cars during carriage by rail ferries has not yet been adequately covered [4, 5].

The aim of the article is to highlight the features of modeling the dynamic loading of the body of a passenger car when transported on a railway ferry. To achieve this aim, the following tasks are defined:

– to carry out mathematical modeling of the dynamic loading of the body of a passenger car during transportation on a railway ferry;

– to carry out computer simulation of the dynamic loading of the body of a passenger car when transported on a railway ferry;

– to conduct a modal analysis of the body of a passenger car when transported on a railway ferry;

– to verify the developed models of the dynamic loading of the body of a passenger car when transported on a railway ferry.

2. Mathematical modeling of the dynamic loading of the passenger car body during transportation by rail ferry

In order to determine the dynamic loads acting on the body of a passenger car when transported by sea, a mathematical model has been drawn up that takes into account the angular displacements of the railway ferry relative to the longitudinal axis (roll) [6, 7]. This type of oscillatory process was chosen for determining, because it has the greatest impact on the strength and stability of the body relative to the deck [8–10]. The design scheme is shown in **Fig. 3**

$$\frac{D}{12\cdot g}\cdot\left(B^2+4\cdot z_g^2\right)\cdot\ddot{q}+\left(\Lambda_\theta\cdot\frac{B}{2}\right)\cdot\dot{q}=p'\cdot\frac{h}{2}+\Lambda_\theta\cdot\frac{B}{2}\cdot\dot{F}(t), \tag{1}$$

where q – the generalized coordinate, corresponds to the angular displacement around the longitudinal axis X of the railway ferry with the cars placed on it; D – weight displacement; B – width; h– side height; Λ_θ – coefficient of resistance to oscillations; z_g – coordinate of the gravity center; p'– wind load; $F(t)$ – the law of action of force that excites the movement of a railway ferry with car bodies placed on its decks.

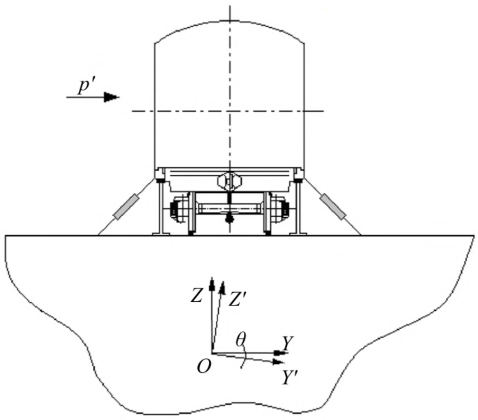


Fig. 3. The design scheme for determining the dynamic loading of the body of a passenger car

The impact of sea waves on the body of a railway ferry with cars placed on board was not taken into account. The model takes into account the dissipative component that occurs when the railway ferry oscillates under sea conditions. Also, the model takes into account the course angles of the sea wave in relation to the body of the railway ferry and the wind load on the surface projection.

The frequency of the sea wave is determined taking into account the course angle to the hull of a railway ferry with cars placed on its decks [8]:

$$\omega=\frac{2\pi\cdot\upsilon}{k_\lambda\cdot L\cdot\cos\chi}, \tag{2}$$

where υ – speed of the railway ferry; k_λ – coefficient depending on the shape of the ship's contours; χ – heading angle of the wave relative to the body of the railway ferry.

In compiling the model, the trochoidal law of motion of a disturbing action (sea wave) on a railroad ferry with car bodies placed on its decks was taken into account [11].

The input parameters of the model are the technical characteristics of the railway ferry and bodies of passenger cars, as well as the hydrometeorological characteristics of the water area. The calculations were carried out in relation to the railway ferry of the type "Mukran" [12, 13], which moves the water area of the Baltic Sea. Hydrometeorological characteristics of the sea area are determined according to the data given in [14].

The solution of differential equations is carried out using the Runge-Kutta method in the MathCad software environment [15, 16].

To solve equation (1), let's the standard function *rkfixed*(*Y0*, *tn*, *tk*, *n*, *Q*) embedded in MathCad. The vector *Y*0 contains the initial conditions. The values *tn* and *tk* determine the initial and final variable of integration, *n* – fixed number of steps, *Q* – a symbol vector [17].

The transition from second order differential equations (1) to first order differential equations (3) is carried out to apply standard algorithms for solving the system in Mathcad.

$$Q(t,y)=\left| \begin{array}{c} y_2 \\ \dfrac{p'\cdot\dfrac{h}{2}+\Lambda_\theta\cdot\dfrac{B}{2}\cdot\dot{F}(t)-\left(\Lambda_\theta\cdot\dfrac{B}{2}\right)\cdot y_2}{\dfrac{D}{12\cdot g}\cdot\left(B^2+4\cdot z_g^2\right)} \end{array} \right|, \tag{3}$$

$$Z = rkfixed(Y0, tn, tk, n, Q).$$

The total amount of acceleration acting on the body of a passenger car when transported by rail ferry is determined

$$\ddot{q}(t)=\ddot{q}_{REG}(t)+g\cdot\sin\theta, \tag{4}$$

where $\ddot{q}_{REG}(t)$ – acceleration, which acts in relation to the regular location of the car on the deck of the railway ferry; θ – roll angle of the rail ferry.

The results of the calculation makes it possible to determine the numerical values of the accelerations, as components of the dynamic load acting on the body of a passenger car when transported on a railway ferry (**Fig. 4**). From **Fig. 4**, it can be seen that the largest value of accelerations acts on the car body at course angles of the wave relative to the body of the railway ferry 600 and 1200 and is about 1.8 m/s^2. That is, it exceeds the magnitude of the accelerations acting on the bodies of passenger cars during operation relative to the main routes [4, 5].

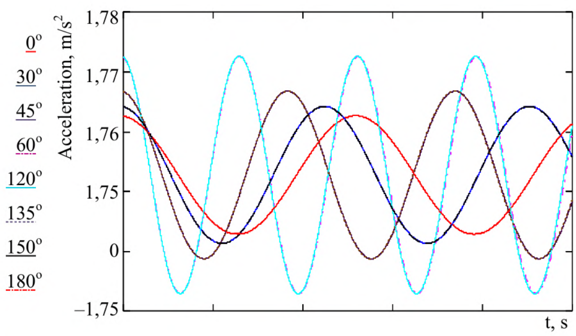


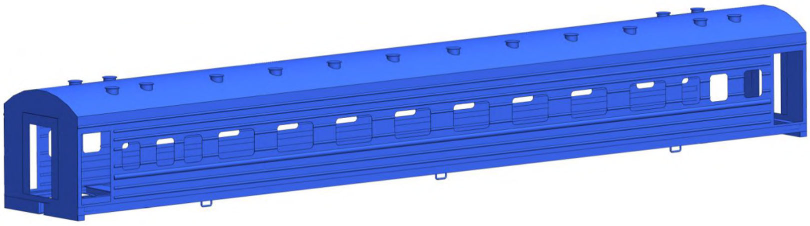
Fig. 4. Acceleration acting on the body of a passenger car when transported by rail ferry

3. Computer simulation of the dynamic loading of the body of a passenger car when transported by rail ferry

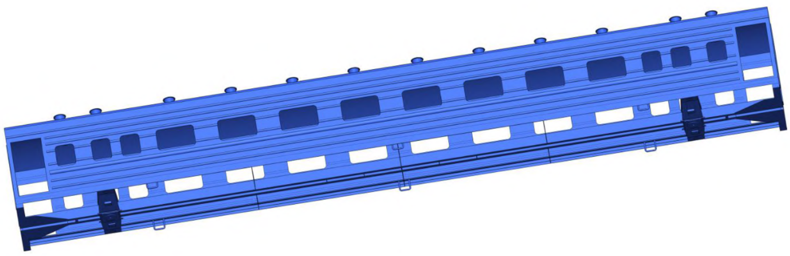
In order to determine the fields of distributions of accelerations with respect to the supporting structure of the body of a passenger car, computer modeling of dynamic loading is carried out during carriage on a railway ferry. For this purpose, a spatial model of the body of a passenger car in the environment of SolidWorks software (**Fig. 5**) is created.

In drawing up the model, structural elements are taken into account, which rigidly interact with each other.

The calculation is carried out using the finite element method implemented in the Cosmos-Works software package [18]. In the compilation of the finite element model, spatial isoparametric tetrahedra are used. The optimal number of elements is determined by the graphic-analytical method. The number of model nodes is 183393, the elements – 520475. The maximum element size is 80 mm, and the minimum – 16 mm. The percentage of elements with an aspect ratio of less than three – 15.1, more than ten – 56. The minimum number of elements in a circle is 12; the ratio of the increase in the size of elements is 1.8.



a



b

Fig. 5. Spatial model of the passenger car body: *a* – side view; *b* – bottom view

In compiling the model, it was taken into account that the body of the car is subject to a vertical static load, P_v^{st}, a wind P_w force, as well as efforts from radar chain screeds P_{cs} (**Fig. 6**). Since the chain ties have a spatial distribution, the efforts that will act on the body through them broke up into components. This takes into account the angles of placement of the chain tie in space.

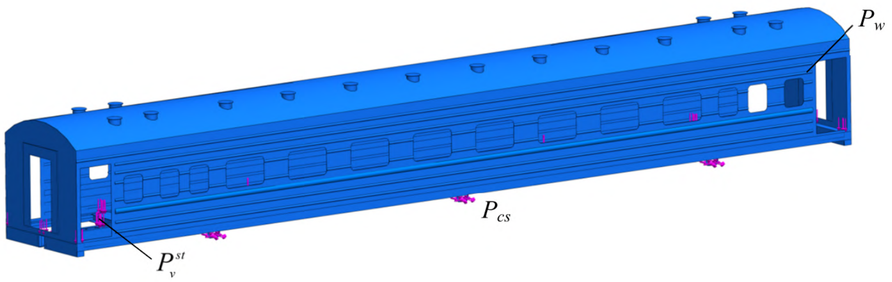


Fig. 6. The design scheme for determining the dynamic loading of the body of a passenger car during carriage by rail ferry

The fastening of the model is carried out in the areas of the body support on the chassis of the car, as well as in the installation zones of the stop-jacks. To do this, the model installed lining, the diameter of which is identical to the diameter of the working part of the mechanical stop-jack (**Fig. 7**). Carbon steel st. 3 are used as the material of the body structure.

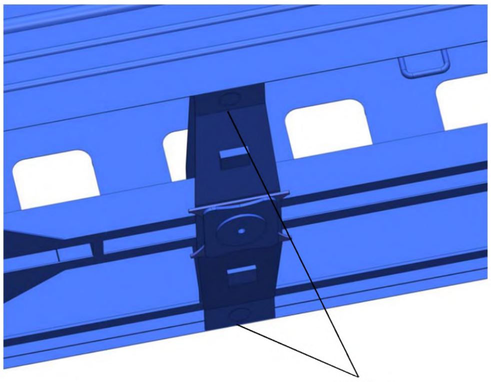


Fig. 7. Placing linings to simulate the bearing of the car body on the mechanical stop-jacks

The calculation results are shown in **Fig. 8.**

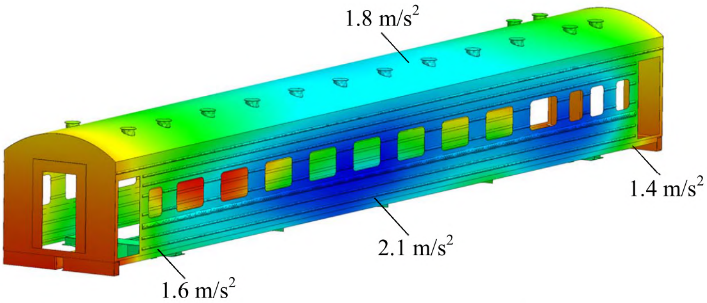


Fig. 8. The distribution of the fields of acceleration relative to the supporting structure of the body of the passenger car

So the maximum values of accelerations are concentrated in the middle part of the side wall of the car body and are 2.1 m/s^2. In the areas of the body supporting the mechanical stop-jacks, the acceleration is about 1.4 m/s^2.

4. Modal analysis of the body of a passenger car when transported by rail ferry

A modal analysis is performed to determine the critical frequencies and vibration modes of the passenger car body. The calculations are carried out in the CosmosWorks software package. The numerical values of the critical oscillation frequencies are given in **Table 1**.

Table 1

Numerical values of the critical frequencies of oscillations of the body of a passenger car when transported by rail ferry

Oscillation form	Frequency, rad/s	Frequency, Hz
1	54.4	8.7
2	107.1	17.1
3	129.5	20.6
4	135.6	21.6
5	149.8	23.8
6	163.2	25.9
7	176.6	28.1
8	208.5	33.2
9	211.7	33.7
10	219.7	34.9

Calculations show that critical frequencies are within acceptable limits. Also, the results of the calculation make it possible to determine the main forms of vibration of the body of a passenger car. For an example **Fig. 9** shows the main forms of vibration of the body of a passenger car when transported by rail ferry. The results are shown in a scale of deformations of 1:50. Transparent color specified initial state of the structure.

Fig. 9. Forms of oscillations of the body of a passenger car when transported by rail ferry: *a* – the first form; *b* – the second form; *c* – the third form; *d* – the fourth form

The resulting vibration modes allow to determine the most loaded areas of the car body and when designing modern passenger car structures to take into account these deformations.

5. Verification of the developed models of the dynamic loading of the body of a passenger car during transportation on a railway ferry

For verification of the developed models, a calculation is made according to the Fisher criterion [19, 20].

$$F_p = \frac{S_{ad}^2}{S_y^2}, \tag{5}$$

where S_{ad}^2 –adequacy dispersion; S_y^2 – reproducibility dispersion.

The variance of adequacy was according to the formula

$$S_{ad}^2 = \frac{\sum_{i=1}^{n}\left(y_i - y_i^c\right)}{f_i}, \tag{6}$$

where y_i^c – calculated value of the value obtained by modeling; f_i – number of degrees of freedom.

$$f_i = N - q, \tag{7}$$

where N – the number of experiments in the planning matrix; q – the number of coefficients of the equation.

The dispersion of reproducibility is determined by the formula

$$S_y^2 = \frac{1}{N}\sum_{i=1}^{n} S_i^2, \tag{8}$$

where S_i^2 – dispersion at each point where parallel experiments are conducted.

The required number of static data is recognized by Student's criterion [21, 22].

$$n=\frac{t^2\cdot\sigma^2}{\delta^2}, \quad (9)$$

where t – tabular value of the Student's criterion; σ – average deviation of a random variable; δ^2 – absolute error of the measurement result.

The input parameter of the model is the roll angle of the rail ferry with the cars placed on it, and the output is acceleration. The calculation results are shown in **Fig. 10**. The trend line equation, which describes the results of mathematical modeling in **Fig. 10** marked y_M, and computer – y_C.

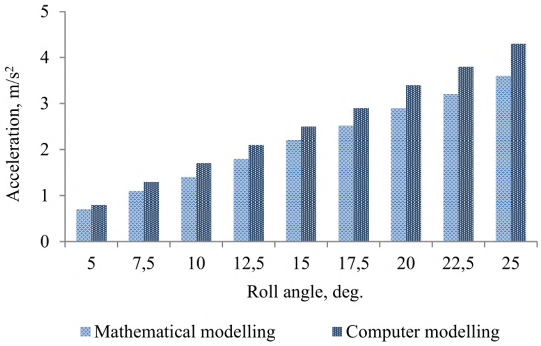


Fig. 10. The results of modeling the dynamic loading of the body of a passenger car when transported by rail ferry

The discrepancy between the results of mathematical and computer modeling in percent is shown in **Fig. 11.**

The maximum discrepancy in this case is about 18 % at a roll angle of rail ferry 100, the smallest – 12 % for a roll angle of 150.

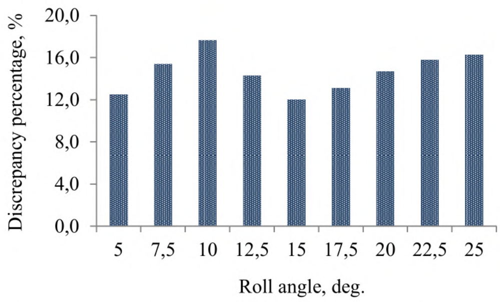


Fig. 11. Discrepancy between the results of mathematical and computer modeling

It is established that with dispersion of reproducibility $S_y^2=0.97$ and dispersion of adequacy $S_{ad}^2=1.38$, the actual value of the criterion F_p=1.4, which is less than the tabular value of the criterion (F_t=3.29). That is, the hypothesis of adequacy is not disputed.

5. Discussion of the research results of the dynamic loading of the body of a passenger car when transported by rail ferry

Studies have allowed to determine the dynamic loading of the body of a passenger car when transported by rail ferry. It has been established that the largest value of accelerations acts on the car body at course angles of the wave relative to the body of the railway ferry 600, as well as 1200, and is about 1.8 m/s^2. That is, it exceeds the magnitude of the accelerations acting on the bodies of passenger cars during operation with respect to trunk routes.

The results of computer simulation show that the maximum acceleration values are concentrated in the middle part of the side wall of the car body and are 2.1 m/s^2. At the same time, in the areas of body support for mechanical stop-jacks, the acceleration was about 1.4 m/s^2.

The developed models are verified by the Fisher criterion.

However, it is important to note that when modeling dynamic loading it is taken into account that the car body is rigidly fixed relative to the deck and carries out movement with it. That is, there are no possible own movements of the car body. Also, the model takes into account the constant speed of the railway ferry.

Further studies need to take into account these limitations. In addition, it is necessary to take into account the stochastic parameters of the disturbing action in the model.

An important stage in the development of these studies is to conduct a physical experiment of dynamic loading of bodies of passenger cars.

These studies will create recommendations for the safe operation of passenger cars in the international rail-water communication. Also, the results will contribute to the creation of modern passenger car structures in the conditions of car-building enterprises.

6. Conclusions

Mathematical modeling of the dynamic loading of the body of a passenger car during transportation on a railway ferry is carried out. It has been established that the largest value of accelerations acts on the car body at course angles of the wave relative to the body of the railway ferry 600 and 1200 and is about 1.8 m/s^2. So the magnitude of the accelerations that acts on the body of a passenger car exceeds the acceleration acting during operation relative to the main tracks;

Computer modeling of the dynamic loading of the passenger car body during transportation on the railway ferry is carried out. The maximum values of accelerations are concentrated in the middle part of the side wall of the car body and are 2.1 m/s^2. In the areas of the body supporting the mechanical stop-jacks, the acceleration was about 1.4 m/s^2;

A modal analysis of the passenger car body was carried out during carriage by rail ferry. The calculation results showed that the critical frequencies are within acceptable limits;

Models of dynamic loading of the body of a passenger car during transportation on a railway ferry have been developed.

It is established that with dispersion of reproducibility $S_y^2 = 0.97$ and dispersion of adequacy $S_{ad}^2 = 1.38$, the actual value of the criterion F_p=1.4. That is, the table value of the criterion exceeds the calculated one. So the hypothesis of adequacy is not disputed.

The research will contribute to the creation of recommendations on the safety of passenger carriages by railway ferries, as well as the manufacture of their modern structures in terms of car-building enterprises.

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