Hierarchical analysis and modelling of regional environmental and economic security

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Abstract. The article analyzes a number of indicators characterizing the environmental and economic state of the region. It is established that the state of the environment has already moved from the category of exogenous parameters for the economic system into the category of intra-economic characteristics, which, first of all, changes the structure and nature of methods of analysis and assessment of the impact of pollution on the environment. The method of hierarchical analysis, which allows to systematize the elements of environmental and economic security of the region, is applied. The mathematical support of the method of analysis hierarchies is considered. To assess the quality of environmental and economic security of the region a hierarchy is built, which provides for the allocation of the criteria of the upper and lower levels. It is proved that the economic basis of regional environmental-economic interests is the ownership of natural resources, and the environmental basis is the integrity of ecosystems in the region. It is proved that the formation and improvement of the mechanism of security should be based on the coordination of environmental and economic interests and the resolution of contradictions between them. The authors proposed an original software product for the justification of the safety parameters of ecological and economic systems. The structure and parameters of the developed decision support system, allowing to carry out the convolution of the group of economic and environmental factors that influence the quality of management decisions, are considered. The hierarchical model built allows the decision maker to form a system of ranked indicators that determine the level of environmental safety of regional environmental-economic systems, and provide a reasoned choice of project alternatives.

The scientific substantiation of the state ecological-economic policy requires the development of a system of mathematical methods and models to describe the processes of man-made pollution of the environment. Problems of environmental and economic security (EES), regulation, administrative and control mechanisms to reduce the negative impact of industrial activity on the environment, the scientific justification of the concept of environmental and economic development of the state and its subjects are considered in the works of national and foreign scientists for the past decades. Analyzed the economic and organizational mechanism of nature management, issues of quantitative assessment of environmental costs of industrial activity and economic efficiency of environmental protection activities, problems of forming an effective territorial system of environmental quality regulation in market conditions; interaction of macroeconomic growth with the state of the environment, state stimulation of investment in the development of environmentally friendly technologies.
Along with this, mechanisms for solving the effective regulation of the security of the ecological-economic system are insufficiently developed and require additional analysis and improvement of algorithms to justify the parameters of the security of ecological-economic systems.

Researches of last years were directed on search of various methods of modeling of the analysis and the decision of problems of management of ecological safety and development of statistical multifactor models according to observational data on a condition of the environment [1-4]. The proposed approaches and methods are mainly devoted to solving a number of problems of forecasting the state of atmospheric air pollution. However, most of the developed forecasting techniques use relatively simple models and have high errors associated with the presence in them of a significant number of assumptions and limitations. The application of more complex models requires substantial time costs and a considerable amount of initial data, which limits the potential possibilities of their use [5-8].

At present, the task of preserving the environment along with economic growth is set, which entails the necessity of creating a new unified parametric space in the system of economic analysis, capable of reflecting both economic development and the state of the environment. So far, the issues of economic development and the state of the environment have not had a unified system of measurements - there were separate statistics of economic development and the accounting of the state of the environment. The first one was dominated by value, monetary indicators, the second one by natural, physical ones. Such situation reflected the general view of the environment as something external to the economy. In modern conditions the state of the environment has already moved from the category of exogenous parameters for the economic system into the category of intra-economic characteristics, which, first of all, changes the structure and nature of methods of analysis and assessment of the impact of pollution on the activities of the enterprise, region, state [9]. The state invests significant resources in fixed capital investments aimed at environmental protection. The dynamics of expenditures on environmental protection and rational use of natural resources in Russia as a whole is shown in figure 1.

**Figure 1.** Investment in fixed capital aimed at environmental protection and rational use of natural resources in Russia in 2000, 2010, 2017-2019 [10].

Expenditures on environmental protection by constituent entities of the Russian Federation (using the example of the Southern Federal District) are shown in figure 2.
The analysis of a number of indicators characterizing the environmental and economic condition of the Volgograd region showed that the region, among the major subjects of the Southern Federal District, is second only to Krasnodar region in terms of expenditures on environmental protection.

Figure 2. Environmental protection expenditures by constituent entities of the Russian Federation (using the example of the Southern Federal District), million rubles.

The total volume of air pollutant emissions in 2019 amounted to 143.6 thousand tons (about 120 thousand tons reduction compared to the base year of 2000), the reduction of captured air pollutants emitted by stationary sources amounted to about over 255 million tons. Discharge of polluted wastewater - about 132 million m3.

Statistical research allowed to establish a direct correlation between economic growth and environmental degradation, on the one hand, and environmental degradation and increase in economic costs of production, on the other hand. In 2019, according to Federal State Statistics Service estimates, the gross regional product (GRP) grew in comparable prices by 121% compared to 2010 and amounted to 961.4 billion rubles. The dynamics of pollutant emissions in Volgograd region is shown in figure 3.

Figure 3. Dynamics of pollutant emissions in Volgograd region in 2000, 2010, 2017-2019 [10].
All emissions to the atmosphere - coming into the atmospheric air and leaving from stationary emission sources - were taken into account. All pollutants entering the atmospheric air both after passage of dust and gas purification facilities (as a result of incomplete capture and cleaning) at organized pollution sources and without cleaning of organized and unorganized pollution sources were taken into account. Accounting of air pollutant emissions was carried out both by their aggregate state (solid, gaseous, liquid) and by individual substances (ingredients). The amount of air pollutants captured includes all types of pollutants neutralized at dust-collecting facilities from their total volume emitted from stationary sources.

The research showed a direct correlation between the influence of environmental protection costs on the level of mortality in Volgograd region. Of course, this estimation is somewhat artificial, since each district of the region has its own specifics, but since there is not enough data specifically for individual districts of the region, the correlation and regression model are built at the level of the region as a whole. As a result of the correlation and regression analysis, the following dependence of mortality on environmental costs was obtained:

\[ Y = -3541.4 - 0.322X, \quad R^2 = 0.82 \]  

(1)

where: \( Y \) is the mortality rate, ppm (the number of deaths per 1 thousand people in the region); 
\( X \) is the cost of environmental protection in the region, million rubles.

The resulting statistical model determines 82% of the variation of the mortality rate (the following statistical data were used for the calculation: the number of deaths in the region for the period, the average annual population in the region for the period, the costs of environmental protection in the region for the period 2010-2019). The results of calculation of multiple correlation [11] showed that the mortality rate in the Volgograd region depends on environmental costs by 79.7% and on pollutant emissions by 83.5%.

At present, at the level of the subjects of the federation it is possible to build an economic system based on environmental priorities through the improvement of the EES system. The conducted research allowed forming the structure of information and methodological support of EES, presented in Table 1.

| Elements | Essence |
|----------|---------|
| 1. Concept | 1.1 Environmental and economic security; 1.2 Decision support system; 1.3 Method of hierarchical analysis and synthesis; 1.4 Priority vectors of alternatives; 1.5 Hierarchy coupling. |
| 2. Goals and objectives | 2.1. Hierarchy focus. |
| 3. Program | 3.1. Regional program to ensure environmental and economic security. |
| 4. System of indicators | 4.1. Economic; 4.2 Environmental; 4.3 Environmental-economic; 4.4. Social. |
| 5. Models | 5.1. Analytical; 5.2. Hierarchical. |
| 6. Tools | 6.1. Decision support system; 6.2 Specialized database; 6.3 Hierarchical structures. |
Methods of data mining are used in different iterations of the decision-making procedure, at the input of the simulation model - at the stages of analyzing the external environment and clarifying the internal structure, and at the output - in strategic planning and operational management in the interpretation of modeling results and in selection procedures. The method of hierarchical analysis and synthesis (HAS) used allows to systematize the elements of the region's EES on the basis of a hierarchical approach, including stakeholders, or by T. Saaty - actors, as well as criteria and alternatives. The construction of a hierarchy for assessing the quality of the EES involves the allocation of the criteria of the upper and lower levels.

The structure of the developed hierarchical model is shown in figure 4.

![Hierarchy of evaluation criteria of environmental and economic security.](image)

The mathematical apparatus of the used method provides the implementation of the analysis and synthesis stages. At the initial stage of hierarchical analysis, the priority vectors of actors $W^A_j$ with respect to the focus of the hierarchy are determined.

At the next stage the matrices of pairwise comparisons of the elements $E_{ij}$ are processed in a similar way. As a result of processing the matrices of pairwise comparisons the set of priority vectors of elements is determined:

$$W^E = \left\{ W^E_{(E_{ij})} \right\}$$

The obtained values of vectors $W^E_{(E_{ij})}$ are used further in determining the priority vectors of alternatives relative to all elements of the hierarchy.

At step 3, the hierarchical synthesis is performed directly, which consists in the sequential determination of the priority vectors of alternatives with respect to the elements $E_{ij}$, which are at all hierarchical levels. Priority vectors are calculated in the direction from the lower levels to the upper levels, taking into account the specific links between the elements belonging to different levels, by multiplying the corresponding vectors and matrices.

The general form of the expression for calculating the priority vectors of the project alternatives $A_i$ is defined as follows:

$$W^A_{E_{ij}} = \left[ W^A_{E_{i1}^{-1}}, W^A_{E_{i2}^{-1}}, ..., W^A_{E_{in}^{-1}} \right] * W^E_{E_{ij}^{-1}}$$
where $W^A_{(e_j^i)}$ - a vector of alternatives priorities relative to the element $E_1^{i-1}$, defining the j-th column of the matrix; $W^E_{(e_j^i-1)}$ - a vector of priorities of elements $E_1^{i-1}, E_2^{i-1}, ..., E_n^{i-1}$, associated with the element $E_j^i$ of the above-level hierarchy [12].

The peculiarity of the described method is that the scales in which the evaluation of the degrees of preference of options for each of the criteria is supposed to be scales of relations, not related to each other and to the priorities of the criteria. Due to the cumbersomeness of numerical calculations within the framework of the applied mathematical apparatus, the specialized computer program "Information system for decision-making support in the sphere of ecological management" [13], which realizes the algorithm of the HAS method, was developed.

The main functions of the developed Decision-making Support System (DMS): selection of the operating mode (Expert or Decision Maker (DM)); making a hierarchy; evaluation of actors and criteria importance (Expert mode); solution of the synthesis problem based on the selected hierarchy; evaluation of alternatives importance by quantitative or qualitative method; graphic visualization of solution results - vector of alternatives priorities (DM mode); storage of hierarchies and tasks in the database.

The database of the developed program consists of nine interconnected tables: actor; actor_rating; alternative; alternative_rating; criteria; criteria_rating; hierarchy (filled by the expert); task (filled by DM); user (system users).

The work of the program begins with the choice of the role - Expert or DM, and entering the login and password. In the Expert mode, the developed DMS system provides the possibility (figure 4): create a new hierarchy; save the hierarchy under another name; set the hierarchy description; select the required number of actor levels; enter a list of actors; compare actors relative to the hierarchy focus or relative to the parent group of actors; set the number of criterion levels; enter a criterion list; set the criterion evaluation type; set the minimum and maximum evaluation value for quantitative type criteria; evaluate criteria relative to actors or supra-criteria; work with actors and criteria.
Figure 5. Working window of the system in the Expert mode: (a) - work with actors; (b) - work with criteria.

The system allows to separately create a new task for a particular hierarchy developed by the Expert; to save the task under a different name; to describe the task; to enter a list of alternatives; to evaluate alternatives according to criteria of benefit and loss hierarchies; to calculate the final evaluations of alternatives according to benefit and loss hierarchies and to display the results in a bar chart; to build a three-sector graph in coordinates of benefits and losses for the given alternatives. The expert interactively determines the relative measure of the importance of alternatives for each group of criteria in the hierarchy (economic, environmental, social) and the focus of the hierarchy (EES level) (table 2).

Table 2. Priority vectors of criteria relative to actors.

| Criteria     | Population | Authority | Business | Enterprise staff |
|--------------|------------|-----------|----------|------------------|
| Economic     | 0.100      | 0.163     | 0.792    | 0.514            |
| Environmental| 0.220      | 0.297     | 0.076    | 0.243            |
| Social       | 0.679      | 0.539     | 0.131    | 0.241            |

As alternatives to ensure the EES on the example of the enterprise oil refining production, were taken: $A_1$ - closing or complete conversion of the enterprise, $A_2$ - installation or modernization of environmental protection, $A_3$ - preservation of the status-quo.

The final estimates of the analyzed alternatives, calculated using the developed program, are presented in the form of bar charts in figure 5. The presentation of the results of the comparison of alternatives ($A_1$, ..., $A_m$) allows for a clearer analysis of their differences in the coordinates "Benefits", "Losses". In the evaluation of benefits dominates with a slight advantage alternative $A_3$ (0.485) over
alternative $A_2$ (0.445), in the evaluation of losses dominates (has the smallest losses) alternative $A_2$ (0.133) (figure 6-a). In the total evaluation of the difference of benefits and losses, alternative $A_2$ dominates (0.313) (figure 6-b).

You can visually assess the ratio of benefits to losses of the alternatives being compared using the three-sector graph, which depicts the alternatives in coordinates of benefits and losses on a colored background, where the colors highlight high risk (the ratio of estimates of losses and benefits is more than two), medium risk (2 to 0.5) and low risk (the ratio is less than 0.5).

Figure 6. Tab "Evaluations of alternatives", which presents the final evaluations in the form of bar charts: (a) Separate values by group of alternatives; b) algebraic sum of both groups of alternatives.
In this case, the decision maker should choose alternative A₂ because it is superior to A₃ by the level of losses and by comparative total and relative indicators, while the superiority of alternative A₂ by the level of benefits is insignificant. Alternative A₁ is significantly inferior to the other alternatives by all indicators. Thus, the developed decision support system, carries out the convolution of economic and environmental groups of factors in the hierarchical model, allowing to build for DM the system of ranked indicators of the level of ecological safety of regional ecological-economic systems.

The hierarchical model built allows the decision maker to form a system of ranked indicators that determine the level of environmental safety of regional environmental-economic systems, and provide a reasoned choice of project alternatives.

Thus, the scientific justification of the state environmental-economic policy required the development of a system of mathematical models to describe the processes of man-made pollution of the environment. The decision-making support system developed on the basis of the constructed mathematical models, allows to realize the hierarchical model providing DM with the information-analytical support of the regional ecological-economic security.

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