Decision-making based on the model of functioning of socio-ecological-economic system

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Abstarct. The development of regional socio-economic and ecological systems requires informed decisions. In this, decision-making authorities can be helped by models of such systems, which include three interrelated subsystems: social, environmental and economic, which may include subsystems of a lower level. The object of the study is hierarchical socio-ecological-economic systems (SEES) with homogeneous performance characteristics at all levels of management. The subject of the study is the characteristics of the processes of influence of factors on the results of the functioning of a hierarchical SEES in order to develop control actions that provide a given level of target indicators. The purpose of the study is to model the functioning of socio-ecological and economic systems based on a multi-level optimization approach under conditions of uncertainty, with the help of which it is possible to find changes in factors that allow improving the goal indicators of the SEES functioning. Based on the constructed models of the state and functioning of complex systems for the regions of the Central Federal District and the Tula Region using statistical data for 2007-2020, a multilevel optimization approach to the management of socio-economic systems was applied, proposals aimed at ensuring the sustainable development of the Tula region in the ecological subsystem were substantiated.

Keywords: socio-ecological-economic systems, model, decision-making, optimization

1 Introduction

Socio-ecological-economic systems are considered as territorial entities in the relationship between the results of social production, the standard of living of the population and the state of the environment [1]. Modeling of such complex systems relies on the use of certain indicators reflecting the results of individual processes and phenomena. The most common indicator at the regional level is the gross regional product (GDP by region). As a rule, it is calculated per capita at purchasing power parity. GDP by region has a high degree of

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generalization and depends on many factors, including the production volumes of industrial enterprises, agricultural enterprises, human resources, etc. In turn, production volumes will depend on the degree of depreciation of fixed assets of enterprises, the level of technologies used, their availability of human resources, etc. Thus, a hierarchical model of the socio-ecological-economic system of a certain territorial entity is consistently formed. However, the model can provide information about the results of the functioning of the elements and subsystems of the SEES, but does not provide information about how and how to change the factors that will improve the target indicators of their functioning. In this aspect, it seems urgent to use models to search for such factors.

The selection and construction of a hierarchy of indicators describing the state of social, ecological, economic or socio-ecological-economic systems is a non-trivial task that researchers have to solve each time in an original way due, on the one hand, to the large variety of these systems, and on the other hand, the variety of approaches to the selection of indicators used by specific researchers. Let's look at examples of indicators used in modeling different systems.

Researchers from China Cheng M. and Liu B. studying the patterns of economic development, proposed a modified model of the production function, which reflects the relationship of private and integral indicators of the socio-ecological and economic system [2]. The authors believe that these particular indicators can be used both to determine the indicators of the region and countries.

When constructing models for the development of territories as a socio-ecological and economic system, researchers can use very specific indicators that, in their opinion, reflect the characteristics of the territory. For example, in Spain, for the socio-ecological system of Fuerteventura, a model has been developed that includes 8 main indicators of sustainable development of the region, including the number of tourists per inhabitant, the ratio between the accommodation of tourists and the permanent population, the proportion of unnatural land formations, a high-quality proportion of vegetation, the local agroecosystem, an indicator of overgrazing, the proportion of the Egyptian vulture population, the proportion of habitats of houbara bustard. The authors built a cognitive model, which is a simplified overview of the Fuerteventura sustainable development model, as well as models for each of the indicators, which made it possible to make a forecast about their changes [3].

Another example reflecting the interdependence of social, environmental and economic factors is a study conducted in Iran to justify decisions on the distribution of energy subsidies [4].

Absolute indicators, for example, in value terms, can be used to study individual areas of activity and the development of regions. An example of this approach in relation to the assessment of the innovation potential of the region is presented in the study of the innovation potential of the regions of the Central Federal District in 2015-2017 [5].

Thus, the choice of indicators used in models of socio-ecological-economic systems and their particular cases is influenced by the goal of researchers [6]. Researchers move from generalized models to particular indicators in cases where it is necessary to evaluate the necessary efforts in individual areas of activity to achieve an overall result. Researchers use both absolute and relative indicators. As a rule, absolute indicators are used for particular tasks. Relative indicators make it possible to form hierarchical dependencies that reflect the hierarchy of socio-ecological and economic systems.

In 2020, Chinese researchers examined a modern model for assessing the socio-ecological and economic system in order to study the welfare of one of the largest economic centers of the China [7]. For their work, they selected 3 main evaluation criteria (magnitude of impact, sensitivity and adaptability), which included 40 indicators of resources, environment, economy and society to build the model they needed. They used the level difference standardization method to standardize the data and eliminate the effect of dimension size on the results. Then they used the entropy method to calculate the index weight value, which made the result more scientifically sound and reasonable.

D.V. Shimanovsky and E.A. Tretyakova model the relationship between the social, environmental and economic subsystems of the SEES, analyzing the growth rates of GDP by region, environmental pollution and the index of social well-being [8].

It can be concluded that models of complex systems are used in one form or another to study the state and functioning of the system, forecast, optimize the state and functioning of the SES, and their choice is determined by the goals and objectives of the study. However, there are a number of problems that have not yet been solved within the framework of existing models describing both economic and socio-economic systems. These include the problems of dimensionality and aggregation of data in cross-industry balance models; averaging of actual data, as well as their reliability and accuracy. Some of these problems can be solved through operational management methods using up-to-date statistical information and optimization models [9].

2 Materials and Methods

To assess the results of the SEES functioning, we will consider the socio-ecological-economic system from the point of view of its hierarchy, where each element identified through its characteristic descriptions belongs to one of the subsystems of a given hierarchy level within the framework of the accepted classification. At the same time, the classification at each level is the same.

The SEES of Russia can be represented in the form of a four–level structure: state – district – region - municipality. At each level, the system can be represented in the form of subsystems, for example: social, environmental and economic subsystems.

Characteristics of the studied hierarchy of indicators describing the state of the regional socio-ecological-economic system include:

1) for the economic subsystem, there are 14 resultative features and 28 factors;

2) for the social subsystem, there are 3 resultative features and 8 factors;

3) for the ecological subsystem, there are 9 resultative features and 8 factors.

In this study, models of resultative features (linear, logarithmic and multiplicative) are constructed, which are subsequently used to form norms (expected) values of the SEES functioning. For the purpose of comparability of indicators evaluated in different units of measurement, the models are brought to a standardized form:

$$\hat{y}_i^* = \sum_{j=1}^{n} C_{i,j} \cdot x_j^* + \sum_{s=1}^{s} D_{i,s} \cdot z_s^* , \qquad (1)$$

$$\ln(\hat{y}_i^*) = \sum_{j=1}^{n} C_{i,j} \cdot \ln(x_j^*) + \sum_{s=1}^{s} D_{i,s} \cdot \ln(z_s^*) , \qquad (2)$$

where n is the number of state factors, S is the number of impact factors, $C_{i,j}$, $D_{i,s}$ are the corresponding weighting coefficients between the i-th resultative features and the j-th and s-th standardized state factors x_j^* and impact factors z_s^*.

The state factors represent the most essential properties of the system at a given time.

Impact factors are a set of controlled factors, the change of which leads to a change in the results of the functioning of the system.

The separation of factors in the models that have a significant impact on the effective attribute allows us to further evaluate the effectiveness of various types (functioning, impact and management).

Management entities can change the impact factors.

When substituting the actual x_j^* and z_s^* values into the model for *k*-th SEES, it is possible to obtain a specific norm for it (the expected value).

The non-linearized model (2) eventually yields a multiplicative model. An exponential model is also used.

The proposed model is the central link of a multilevel optimization approach to the operation of the SEES, which includes the following stages [10].

1. Formalized description of the SEES.

2. Identification of the results of the SEES functioning at each of the levels, state factors and impacts (control factors).

3. Building models of the relationship between the effective features of the elements (classes, levels) of the SEES and the conditions by which the normative (expected) values are determined, which are the purpose of the SEES functioning.

Communication models can be presented for elements in the form of production functions, for subsystems (classes) – in the form of aggregated production functions.

4. Evaluation of partial and integral performance indicators, efficiency and harmony of the SEES functioning, forming a system of universal indicators.

5. Selection of effective features that do not correspond to the normative values, which act as criteria for the satisfactory functioning of the elements and subsystems of the SEES.

If such conditions are met, the operation of the SEES is considered satisfactory. Otherwise, it is necessary to optimize the functioning of its elements and subsystems. The conditions are also applicable for the case when the performance indicators significantly exceed one. In the first approximation, only elements for which performance indicators are less than one can be considered.

6. Optimization of factor features implies the search for such values at which the considered effective features would reach their standards (or be within acceptable limits), that is, the goals of functioning would be achieved.

If only normative models are used, then the problem of intensive development is solved: how much overspending (underutilization) of state and impact factors is observed in the element, subsystem of the SEES.

In general, the optimization model can be represented as a ratio:

$$F_{v_p}(t_0)=[\sum_{p=h}^{1}(\mu_{H_{Ap}}\cdot(1-H_{Ap})+\mu\cdot\left|y^{0}_{p,v_p,s_q}(t_0)-\tilde{y}^{0}_{p,v_p,s_q}(t_0)\right|+\sum_{i=1}^{I}\mu_i\cdot\left|(y^{0}_{p,i,v_p,s_q}(t_0)-\tilde{y}^{0}_{p,i,v_p,s_q}(t_0)\right|)]\times$$
$$\times(1+\sum_{i=1}^{I}\sum_{j=1}^{J}\omega_{i,j}\cdot\left|\Delta x^{0}_{p,i,v_p,s_q,j}(t_0)\right|+\sum_{i=1}^{I}\sum_{u=1}^{U}\eta_{i,u}\cdot\left|\Delta z^{0}_{p,i,v_p,s_q,u}(t_0)\right|)\to\min. \tag{3}$$

Here H_{Ap} is a coefficient of harmony, $\mu_{H_{Ap}}$, μ, μ_i, $\omega_{i,j}$, $\eta_{i,u}$ – the weight of the coefficient of harmony (coefficient of harmony is by the difference between the unit and the ratio of the average and standard deviation of the quotients (determined by the ratio of unified – reduced to a scale from 0 to 1 after the standardization procedure – actual $y^{0}_{p,i,v_p,s_q}(t_0)$ and normative $\tilde{y}^{0}_{p,i,v_p,s_q}(t_0)$ resultative features) or integral (integral indicators which are determined by the ratio of quadratic convolutions of particular actual and normative results and their correlation matrix – $y^{0}_{p,v_p,s_q}(t_0)$, $\tilde{y}^{0}_{p,v_p,s_q}(t_0)$) resultative features; integral, partial performance indicators, changes in the state factors $\Delta x^{0}_{p,i,v_p,s_q,j}(t_0)$ and impact factors $\Delta z^{0}_{p,i,v_p,s_q,u}(t_0)$, respectively, and the system of restrictions; *h* is the number of *p* levels, which in this context corresponds to the lowest level of the SEES. In this case $y^{0}_{p,v_p,s_q}(t_0)$ is determined by the sum of the result calculated from the communication model constructed from the data for the selected subject, and the random component in accordance with the formula (4):

$$y^{0}_{p,(p-1),v_p,s_q}(t_o) = [\tilde{y}^{*}_{p,(p-1),v_p,s_q}(t_0) + \varepsilon^{*}_{p,(p-1),v_p,s_q}(t_0)]^{0}, \quad (4)$$

where $\tilde{y}^{*}_{p,(p-1),v_p,s_q}(t_0)$ is the standardized value calculated using a production function $\tilde{y}^{*}_{p,(p-1),v_p,s_q}$, which constructed from data for v_p -th element; $\varepsilon^{*}_{p,(p-1),v_p,s_q}(t_0)$ is residual – the value of a random variable of the corresponding econometric equation; «0» are normalized (reduced to a scale from 0 to 1) values.

The results of assessing the functioning of regions with the help of partial and integral indicators can be useful to regional governments for subsequent analysis and synthesis of solutions that make it possible to ensure compliance of the actual and normative values of the effective features with a given degree of accuracy by changing and (or) intensifying the use of factors included in the developed models.

3 Results

Data for 17 regions of the Central Federal District for the periods 2007-2020 were used as an information base to build regulatory models of the functioning of elements of the SEES level.

The models of SEES functioning in the Central Federal District and the Tula region are of the same type. Descriptions of variables for constructing models are presented in [1, 11].

Communication between subsystems is carried out through resultative features, as well as state and impact factors, which in turn can act as a result of the functioning of an element of the subsystem.

For example, the factor "discharge of polluted wastewater into surface water bodies", which affects the resultative feature" remaining life expectancy index" of the social subsystem, is the resultative feature of the functioning of the subsystem "water" of the ecological subsystem. At the same time, it can be seen that the signs characterizing the elements of one subsystem may be factors that relate to the signs of other subsystems (for example, the volume of GDP by region per capita is the resultative feature of a social subsystem depends on the total expenditures of the consolidated budget); the same feature can describe different elements of the subsystem (for example, the factor – the average annual population – describes the behavior of elements whose functioning results in the volume of GRP under section J(K) – Financial activity (market services sector or project subsystem) and an element of the ecological subsystem (subsystem "water") characterized by effective the sign "discharge of polluted wastewater into surface water bodies". Some signs may also apply to social and economic subsystems (for example, GDP by region per capita in PPP in US dollars).

Thus, the constructed model of the SEES functioning for the regions of the Central Federal District (the normative model is the same for all regions of the Central Federal District) and the Tula region (the model built under the data only for the Tula region differs in the evaluation periods and values of the model parameters), is a set of models for elements in the form of production functions and subsystems in the form of aggregated production functions, which makes it possible to consider the SEES as an integral system with many interconnections and to model the behavior of the SEES,

With the help of the model, it is possible to evaluate and analyze the results of the functioning of the elements and subsystems of the SEES and the socio-ecological-economic system as a whole.

According to the selected performance indicators, it is possible to draw up a socio-ecological and economic portrait of the functioning of the Central Federal District regions, and their visual representation and a fairly simple method of interpreting the results allows it to be used in the activities of regional management bodies in order to develop management decisions, including within the framework of a multi-level optimization approach.

If we consider the subsystems as a whole, then due to the multi directional (more or less than the norm which is equal one) of the particular indicators of the elements of subsystems, the values of integral indicators characterizing the functioning of subsystems are smoothed out due to averaging, however, with a more detailed analysis (not on the slice of subsystems), the imbalance is increasingly obvious. The worst results in 2020 were shown by the following indicators: the intensity of waste generation (0.000), wholesale and retail trade (0.571); mining. The best results were shown by the indicators: the volume of recycled and consistently used water (1,796); the capture of air pollutants coming from stationary sources (1,547); the volume of waste use and disposal (1,537).

On the basis of the constructed models: normative models (according to data for a set of regions of the Central Federal District) and models for the Tula region (according to data for the region), the problem of multi-criteria optimization was solved. The problem is solved for the social, ecological and economic subsystems of the Tula region in two versions: models with restrictions and without restrictions on the parameters of the models are used. In order to take into account the homogeneity of regional development on the territory of the Central Federal District, models with restrictions on parameters were used.

Since optimization was carried out only for the Tula region, the "district" level was not taken into account.

The sum of performance indicators characterizing the results of the functioning of the elements of the optimized subsystems was chosen as the target function. The system of restrictions on factors included changes in the positive and negative sides, corresponding to the increments of factors in the previous period. Moreover, a number of the same factors were contained in different private models. Additional non-linear restrictions were imposed on the effective features, the values of which after optimization should not be less than the values before optimization. The values of negative signs (for example, emissions of pollutants) after optimization should not be greater than the initial values.

Restrictions were imposed: on the indicator of discharge of polluted wastewater into surface water bodies, since it acts both as an effective sign for the ecological subsystem and as a factor for the social subsystem; restrictions linking the average annual population, the coefficient of natural growth and migration growth; restriction on the correspondence of the profitability index – GRP per capita in PPP of US dollars – and the GDP by region volume (total), determined by the amount of GRP according to the NACE sections, and adjusted for inflation and adjusted to the level of 2007, since they are interdependent; restrictions linking the volume of shipped products of own production and the index of industrial production.

Optimization was carried out for all signs, that is, signs for which the corresponding performance indicators were both greater and less than one.

Sequential quadratic programming with constraints, the Newtonian method of solving the Lagrange system was used as an optimization algorithm.

Optimization of the ecological subsystem of the Tula region included 9 indicators (Table 1).

Table 1. Changes in performance characteristics: ecological subsystem.

Model	Value before optimization	Value before optimization	Change feature
Air pollutants, thousand tons	190,5	187,684	-2,816
Capture of air pollutants from stationary sources, thousand tons	615	618,925	3,925
The use of fresh water, million cubic meters	221	221,552	0,552
Volume of circulating and consistently used water, million cubic meters	2181	2181	1,233E-07
Discharges of polluted waste water into surface water bodies, million cubic meters	152	151,779	-0,221
Waste generation of production and consumption, thousand tons	11512	11512	0,000
Waste storage and disposal, thousand tons	838	838	0,000
Waste use and decontamination, thousand tons	8490	8490	0,000
Waste intensity, cubic meters / person	4,577	4,573	-0,004

Source: the authors.

4 Discussion

As a result, it was found that regulatory actions are required for four indicators in order to ensure optimal values for the sustainable development of the Tula region. In particular, it is necessary to reduce emissions of pollutants into the atmosphere by 2,816 thousand tons per year, as well as to reduce the discharge of polluting wastewater into surface water bodies by 221 thousand tons. m^3.

In addition, the improvement of the environmental situation in the region will be facilitated by an increase in the capture of air pollutants coming from stationary sources by 3,925 thousand tons per year and an increase in the use of fresh water by 552 thousand tons.

To ensure an increase in the use of fresh water by 552 thousand m^3, it is necessary to increase the production of electricity by 100 thousand kV-h.

The construction and commissioning of waste processing plants with a capacity of at least 6665.6 thousand m^3 per year (taking into account the intensity of waste generation of 4,573 m^3/person per year and the average annual population of 1,457.6 thousand people) should contribute to reducing the level of pollution.

5 Conclusion

The study solves the problem of multi-criteria optimization. The values of changes in factors that will improve the target indicators of the functioning of the SEES have been obtained. The results of the study can serve as recommendations to different level administrations by developing activities aimed at securing long-term sustainability of regions.

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