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Mathematical models of a multi-criteria problem of reengineering topological structures of ecological monitoring networks

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ABSTRACT

The article deals with the theoretical aspects of the problem of reengineering the topological structures of terrestrial ecological monitoring networks. As a result of the analysis of the current state of the problem, it was revealed the *need to change* the network of monitoring points, *to increase* requirements for the efficiency and accuracy of observations, as well as to do the more advanced technologies for collecting, processing, storing and transmitting information. All this is possible due to reengineering of existing monitoring networks. This requires the improvement of network system optimization technologies and their software in terms of taking into account the features of the reengineering problem, as well as the mathematical models and methods used for this. To solve the problem of reengineering of terrestrial monitoring networks, an aggregative-decomposition approach is proposed. The approach is divided into a set of tasks considering their interconnections in terms of input and output data. This made it possible to define a set of tasks that form the basis of reengineering procedures. To increase the efficiency of technologies for computer-aided design and reengineering of networks, a set of mathematical models is proposed that covers the main stages of their life cycles. The article discusses: a systemological model of iterative technology for obtaining design solutions; analytical models for evaluating the properties of network reengineering options in terms of efficiency, reliability, survivability and costs; models for identifying effective options for network reengineering based on Karlin and Germeier theorems; a model for evaluating the local properties of options in the form of a utility function of local criteria; model of scalar multicriteria estimation of network reengineering options based on utility theory. The utility function makes it possible to implement both linear and non-linear (including Z- and S-shaped) dependencies on their values. For the practical implementation of models of multicriteria problems of reengineering of topological structures of networks, it is proposed to use the method of generation of effective design solutions in parallel with the generation and the method of comparator parametric synthesis of the scalar multicriteria estimation function. The performance and efficiency of the proposed mathematical models and methods are demonstrated by examples of solving the problems of subset selection of Pareto-optimal options for building networks and parametric synthesis of the scalar multicriteria estimation function. The application in practice of the proposed set of models and methods will increase the degree of automation of network reengineering processes, reduce the time for solving the problem of multi-criteria choice due to the reduction in the time complexity of the analysis procedures, and increase the stability of the decisions made by compromising their choice only from a subset of effective ones.

Keywords: Environmental monitoring network; design technology; reengineering; making decisions; multiobjective optimization

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INTRODUCTION

Ensuring safe conditions for the development of human society requires systematic observation, control and evaluation of the impact assessment of anthropogenic objects on the state of the environment. To solve such problems, systems of integrated environmental monitoring are used all over the world [1]. The main purpose of create such systems is to obtain, register and operatively transfer data on the state of the environment for analysis [2, 3]. Using of automated technologies for measuring the parameters of the state of control objects for this purpose allows continuous data collection with minimal human intervention [4]. Real-time continuous data collection technologies occupy an important place in hydrological and radiation analysis, assessment of the consequences of natural disasters in weather forecasting [5].

Depending on the scale and characteristics of the objects of control, networks with different structures and network technologies are used for transfer data in monitoring systems. According to significant costs required for the creation and operation of monitoring networks, the irrationality of their build options can lead to significant economic losses.

Improving the means of collect, transfer and process information set the conditions for improving the efficiency of existing networks. Particularly, achievements in the field of electronics allow the use of cheaper data recorders, means of their preprocess and transfer [6].

An increase the number of control points, an increase the requirements for the operativity and accuracy of observations, advent of more advanced technologies for collect, process, store and transfer information at a certain stage leads to the inefficiency of existing options for build networks. Optimization of networks in such circumstances is carried out by their reengineering [7]. The reengineering process involves solving a complex of problems of optimize the network structure, network topology, the parameters of its elements and data transfer channels, enhancement of the technologies for collect, transfer and process information. Monitoring practice use a relatively small amount of information technology, and the parameters of networks are determined by the structure and placement of their elements. With this in mind, the main difficulties in choose a variant of network reengineering arise when solve problems of optimize their topological structures. Such tasks are solved according to a variety of functional and cost indicators, considering numerous structural, parametric, technological, and economic constraints, and have specific differences from traditional design tasks [8]. To improve the performance of ecological monitoring projects, it is necessary to develop a set of effective mathematical support models the adoption of multi-criteria design decisions [9, 10], [11]. Modern technologies for design and reengineer networks involve the generate and analysis of a huge number of options for their construction [12]. Existing mathematical models and methods of multi-criteria choice are focused on the use of expert evaluation of relatively small sets of alternatives [9, 10], [11, 13], [14, 15]. In this regard, there is a need to develop and use mathematical models and methods for interactive, human-machine technologies that complement the knowledge and experience of designers (the person who is makes the decision) with the capabilities of modern computing tools. Combining the advantages of expert methods and computer technology is implemented in intelligent decision support systems [16].

LITERATURE REVIEW

A characteristic feature of most environmental monitoring networks is their significant territorial dispersal [7]. Their cost and functional characteristics are largely determined not only by the parameters of their structure, but also by their topology (territorial distribution of elements). This is a characteristic feature of the so-called distributed objects [12]. In the process of optimize options for constructing distributed objects, together with traditional task of structural synthesis, it is necessary to solve the problems of their topological optimization.

To assess the quality of options for building networks, the methodology of functional cost analysis is used [16]. The main goal of reengineer is to maximize the efficiency of the network building option $s = <E, R, G>$, determined by the ratio of the effect of the use $Q(s)$ and resources spent on it $C(s)$ [12]:

$$Q(s) = F_1(E, R, G), \tag{1}$$

$$C(s) = F_2(E, R, G), \tag{2}$$

where: E, R, G is the set of network elements, connections (relations) between them and their topology; F_1, F_2 is some mappings establishing estimates of the effect of using the network $Q(s)$ and resources spent on it $C(s)$.

The practical use of estimates (1)-(2) requires a structural-parametric synthesis of mappings F_1 фтв F_2. The functional effect of using the network in the general case is a non-decreasing function of the resources spent to achieve it $\bar{Q}(s) = F[\bar{C}(s)]$ (where $\bar{Q}$ and $\bar{C}$ is generalized scalar estimates of effect and costs) [16].

At the initial stage, in conditions of restrictions on the effect indicators $\bar{Q}(s) \geq \bar{Q}^*$ and (or) costs $\bar{C}(s) \leq \bar{C}^*$ problem of network reengineer can formally be represented as follows:

$$s^o = arg \max_{S \in S^*} [\bar{Q}(s) / \bar{C}(s)] :$$

$$\bar{Q}(s) \geq \bar{Q}^*, \ \bar{C}(s) \leq \bar{C}^*, \tag{3}$$

where: $\bar{Q}^*$, $\bar{C}^*$ are specified boundary values for generalized estimates of effect indicators and costs; $S^* = \{s\}$ *is* the set of valid network reengineering options.

Particular cases of problem (3) are the problems of maximizing the effect of using the network under given restrictions on resources and minimizing costs under given restrictions on the functional characteristics of the network [16]:

$$s_1^o = \arg\max_{s\in S^*}(\bar{Q}(s):\ \bar{C}(s) \le \bar{C}^*), \tag{4}$$

$$s_2^o = \arg\min_{s\in S^*}(\bar{C}(s):\ \bar{Q}(s) \ge \bar{Q}^*). \tag{5}$$

The structural complexity of monitoring systems and the close interrelation of their optimization tasks do not allow creating their solid formalized description and finding an effective reengineering option using it within a single project procedure. Based on this, the network description is divided into hierarchical levels and aspects according to the degree of detail, and the reengineering process is divided into groups of design procedures [17]. The procedures selected in this case allow obtaining and transforming descriptions (design decisions) regarding the selected levels and aspects with their subsequent aggregation to obtain decisions on the reengineering option.

From the standpoint of the aggregative-decomposition approach, the problem of network reengineering as a whole can be considered as a certain meta-task consisting of a set of tasks $Task_i^l$, $i=\overline{1,i_l}$, related to different levels of decomposition $l=\overline{1,n_l}$, with their relationships according to the initial data and the results of the decision [17]:

$$MetaTask = \{Task_i^l\}, Task^l = \{Task_i^l\}. \tag{6}$$

Each of the reengineering tasks $Task_i^l$, $i=\overline{1,i_l}$ can be represented as an input data converter In_i^l in the output Out_i^l:

$$Task_i^l : In_i^l \to Out_i^l,\ l=\overline{1,n_l},\ i=\overline{1,i_l}\ . \tag{7}$$

Evaluation of the properties of the resulting reengineering options $s \in S^*$ produced using a variety of local functional and cost criteria $K(s) = [k_1(s), k_2(s), ..., k_m(s)]$.

To improve the accuracy of solutions to the structure optimization problem $Task_{OS}^l$ and network topology $Task_{OT}^l$ it is advisable to decide jointly [12].

The task of the optimizing $Task_{OS}^l$ is devoted to determining the best option for building a network s_{ER}^o by adding additional variant definitions s_{AB} with selected operating technology $A = \Xi_A(E, R)$ and parameters of elements and links $B = \Xi_B(E, R)$ optimal number of elements $|E|^o$ and connection diagram between them R^o:

$$\begin{aligned} &Task_{OS}^l : \{A, B, S^*, K, Q^*, C^*\} \to \\ &\to \{|E|^o, R^o, s_{ER}^o, K(s_{ER}^o)\}. \end{aligned} \tag{8}$$

The task of optimizing the topology of elements and links $Task_{OT}^l$ dedicated to determining the best option s_G^o by adding additional variant of building a network with selected sets of elements E, diagram of connections between them R, their parameters B and network operation technology A best topology G^o:

$$\begin{aligned} &Task_{OT}^l : \{E, R, A, B, S^*, K, Q^*, C^*\} \to \\ &\to \{G^o, s_G^o, K(s_G^o)\}. \end{aligned} \tag{9}$$

The ranking of reengineer options by a variety of indicators is traditionally carried out based on the paradigm of maximize their utility [16]. In computer-aided design technologies use two approaches to solve it: sort alternatives and choose the best option by the decision maker; sort alternatives and choosing the best option using a generalized efficiency criterion. In both approaches, each option from the set of acceptable ones $s \in S^*$ is assigned some assessment of its usefulness (value), $P(s)$ the number which determines the order of the options by their value [16, 18]:

$$\begin{cases} \{\forall s, v \in S^* : s \sim v \leftrightarrow P(s) = P(v); \\ s \succ v \leftrightarrow P(s) > P(v); \\ s \ge V \leftrightarrow P(s) \ge P(v). \end{cases} \tag{10}$$

The task of choosing the best option in this case is considered as the problem of maximizing the generalized utility function:

$$s^o = \arg\max_{s\in S^*} P(s). \tag{11}$$

In the second approach, for the quantitative assessment of options by expert methods, an additive convolution of local criteria or a function built based on the Kolmogorov-Gabor polynomial is traditionally used [16].

The additive function-convolution of local criteria is represented as:

$$P(s) = \sum_{j=1}^{m} \lambda_j \xi_j(s), \tag{12}$$

$$\xi_j(s) = \left[\frac{k_j(s) - k_j^-}{k_j^+ - k_j^-}\right]^{\mu_j},\ j=\overline{1,m}, \tag{13}$$

where: λ_j, $j=\overline{1,m}$ are criteria importance coefficients $k_j(s)$, $\lambda_j \geq 0$; $\sum_{j=1}^{m}\lambda_j = 1$; $\xi_j(s)$ – the value of the utility function of the local criterion $k_j(s)$; k_j^+, k_j^-; $j=\overline{1,m}$ are the worst and best values of the j-th local criterion; μ_j is a parameter that determines the type of dependence (13): convex, linear or concave.

The additive convolution of local criteria (12) does not adequately take into account all the preferences of the decision maker. When using a function built on the basis of the Kolmogorov-Gabor polynomial [16], the problem of selecting its parameters arises. The disadvantage of utility functions of local criteria of the form (13) is the impossibility of implementing with their help Z- and *S*-like dependencies that take place in many practical situations.

In decision-making problems, the choice of the best option is carried out on a given small set of options [9, 10], [11, 13], [14, 15], [16, 19]. At the same time, in the problems of designing and reengineering networks, the vast majority of the analyzed feasible options are inefficient (dominated). There is a problem of selection of a subset of only effective options on the set of admissible options [18].

The given models of tasks of reengineering of structures and topology of monitoring networks (8)-(9) determine only the interrelations of tasks in terms of variables and parameters. For their practical use, it is necessary to solve the problems of structural-parametric synthesis of relationships, which allow obtaining quantitative estimates of options for a set of functional and cost indicators, evaluating decision makers' preferences for a certain indicator and the entire set of indicators.

PURPOSE OF THE ARTICLE

Features of modern technologies for designing monitoring systems show a growing trend towards the universalization of mathematical support for the tasks of supporting the adoption of multi-criteria decisions.

The purpose of this article is to improve the efficiency of technologies for automated design of ecological monitoring networks by developing universal mathematical models of multicriteria problems of reengineering topological structures related to the main stages of their life cycles.

The article considers the problem in the following formulation. For the technology of reengineering of centralized terrestrial ecological monitoring networks, it is necessary to select or improve a set of mathematical models covering the main stages of their life cycles: a systemological model of iterative technology for obtain design solutions; analytical models for evaluating the properties of network reengineering options for a variety of functional and cost indicators; models for identifying effective options for network reengineering; a model for evaluating the local properties of options in the form of utility functions of local criteria, which makes it possible to implement both linear and non-linear (including Z- and S-shaped) dependencies on their values; model of scalar multicriteria estimation of network reengineering options based on utility theory.

TECHNOLOGY MODEL FOR OBTAIN A DESIGN SOLUTION

Based on the formalization of the goals of reengineering of the monitoring network and their decomposition into complexes of interrelated tasks (6), a network model of the basic task is proposed [17]. The set of possible paths on such a model represents the set of submodels that can be formed from its components. The degree of aggregation of the obtained models will be determined by the efficiency of the optimization methods used, the time reserve for solving the problem, and the performance of the computer technology used. Based on the network model, a logical scheme for obtaining a design solution is built, which determines the sequence of solving network reengineering tasks.

To define a scheme $CirDes$ it is necessary to define five sets:

$$CirDes = < Tasks, In, Res, DesDec, ProcDec >, \quad (14)$$

where: $Tasks = \{ Task_i^l \}$ is a ordered set of network reengineering problems (6); $Task_i^l$ is i-th task l-th decomposition levels; In is set of initial task data; Res is task constraints; $DesDec$ is many design solutions (reengineering options); $ProcDec$ – mapping (decisive procedure), which assigns to each pair $< InDat, Res >$ a non-empty subset of design decisions $DesDec$.

The entire set of monitoring network reengineering tasks is completely solvable if there are design procedures $ProcDec_i^l$ for the entire set of identified tasks $\{ Task_i^l \}$ and each design solution is unique:

$$\left| ProcDec_i^l (In_i^l, Res_i^l) \right| = 1, \; l=\overline{1,n_l}, \; i=\overline{1,i_l}. \quad (15)$$

In the process of analyzing the interrelations of the complex of selected reengineering tasks (6), we will represent each of their models in the following form:

$$ModTask_i : \{ InDat_{iE}, InDat_{iI}, Res_i \} \rightarrow \\ \rightarrow DesDec_i,\; i=\overline{1,N}, \qquad (16)$$

where N is the total number of tasks outlined as a result of the decomposition of the network reengineering problem.

Based on the results of the analysis of the network model (16), the sequence of cells in the scheme for solving the problem of network reengineering is determined by constraints, input and output data:

$$ModTask_1 \rightarrow ModTask_2 \rightarrow ... \rightarrow ModTask_N . \quad (17)$$

The chain of tasks (17) forms the basis of a sequential scheme for solving the reengineering problem. Its implementation requires redefining the initial data of the tasks $Task_2$, $Task_3$, …, $Task_N$. For these problems, only locally optimal solutions can be obtained based on predictive or expert input data $InDat_i$ and constraints Res_i $i=\overline{2,N}$.

To solve reengineering problems (17), it is proposed to use an iterative logic scheme that implements alternating procedures for generating, analyze options, and choose the best one (Figure) [17].

The use of such a scheme makes it possible to form the missing initial data $InDat_i$ based on the results of decisions obtained at the previous iteration. At the same time, the quality of solutions is improved, both for particular tasks and for the general tasks of reengineering the monitoring network.

MODELS FOR EVALUATING INDIVIDUAL PROPERTIES OF REENGINEERING OPTIONS

Regardless of the decision-making approach used in the implementation of computer-aided design technology, models for evaluating functional and cost characteristics $k_j(s)$, $j=\overline{1,m}$ are needed for all generated alternatives $s \in S^*$.

Consider the problem of reengineering the topological structure of a three-level centralized regional network of environmental monitoring [8]. The network consists of a center for collecting and processing information, nodes that serve to concentrate and pre-process information from control posts.

Given: set of elements (center, nodes, control posts) of the existing network $I=\{i\}, i=\overline{1,n}$; variant of the topological structure of the existing network $s' \in S^*$ (where S^* is the set of valid options), specified by the locations of the elements, node and center (the center is located on the basis of the element $i=1$); as well as the connections between the elements, nodes and the center $[s'_{ij}]$, $i,j=\overline{1,n}$ (where $s'_{ij}=1$, if there is a direct connection between the elements i and j, and $s'_{ij}=0$ – otherwise); costs for the create or upgrade of nodes $[c_i]$, $[d_i]$, $i=\overline{1,n}$ and connections between elements of the network $[c_{ij}]$, $[d_{ij}]$, $i=\overline{1,n}$.

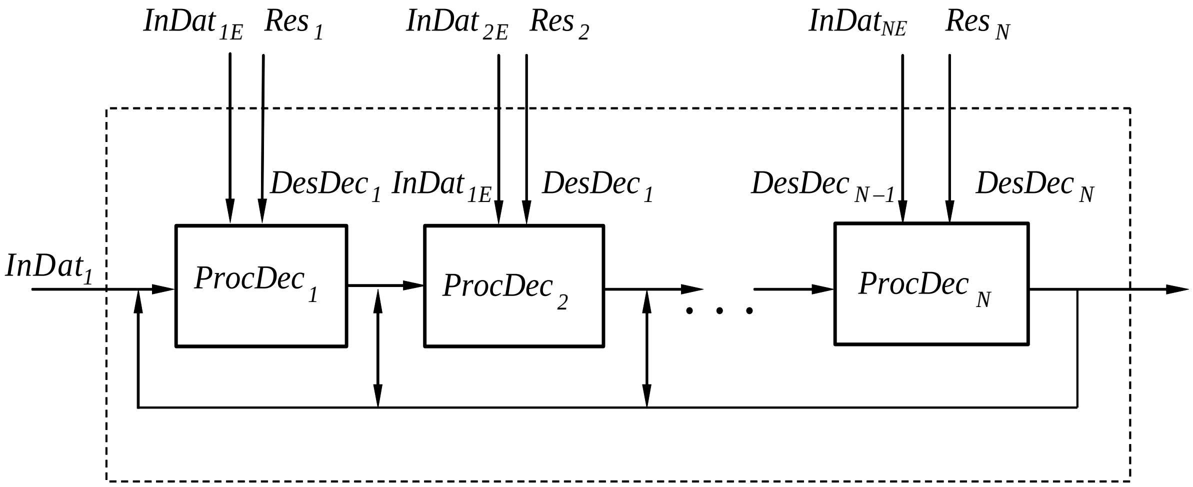

Figure. **Iterative logic scheme for obtaining a design solution**

Source: compiled by the authors

It is necessary to determine the best option for reengineering the topological structure of the network in terms of efficiency (time of obtaining information), reliability, survivability and costs $s^o \in S^*$.

The set of valid options for build a centralized three-level network is given by the conditions:

$$S^* = \{ s \} = \begin{cases} [s_{ij}],\ s_{ij} \in \{0,1\},\ i,j = \overline{1,n},\ s_{11} = 1; \\ \sum\limits_{i=j}^{n} s_{ij} \ge 1\ \forall j = \overline{1,n}; \\ \sum\limits_{j=1}^{n}\sum\limits_{i=j}^{n} s_{ij} = n + \sum\limits_{i=1}^{n} s_{ii}, \\ s_{ii} = 1 \rightarrow s_{i1} = 1\ \forall i = \overline{1,n}; \\ s_{ii} \wedge s_{ij} = 1 \rightarrow ij = arg \min\limits_{1 \le i,j \le n} c_{ij}\ \forall i,j = \overline{1,n}. \end{cases} \qquad (18)$$

The reengineering option is given by the count of nodes u in it, their places of location and the scheme of connections between elements, nodes and the center $[s_{ij}]$, $i,j = \overline{1,n}$.

At the same time, it is considered that: network nodes are located at the base or in close proximity to control posts; posts are connected to nodes in terms of minimum costs (distance); volumes of requests to each network post are equal between $\alpha = [\alpha_i],\ \alpha_i = const$, $i = \overline{1,n}$; volumes of responses from each of the posts are equal $\beta = [\beta_i],\ \beta_i = const$, $i = \overline{1,n}$.

As a criterion of efficiency $k_1(s)$, we use the time of obtaining monitoring data. Then the maximum network efficiency will correspond to the minimum time for obtaining monitoring data from the center upon request:

$$k_1(s) = \left\{ \tau^C + \frac{\bar{\alpha}}{\gamma_1} + \tau^E + \frac{\bar{\beta}}{\gamma_2} + \right. \\ \left. + \left(\frac{\bar{\alpha}}{\gamma_1} + \frac{\bar{\alpha}}{h_1} + \frac{\bar{\beta}}{h_2} + \frac{\bar{\beta}}{\gamma_2} \right) \sum_{j=1}^{n}\sum_{l=j}^{n} s_{jl} s_{jj} \right\} \rightarrow \min_{s \in S^*}, \qquad (19)$$

where: τ^C, τ^E is the time for issuing a request by the center and receiving information about the monitoring object; $\bar{\alpha}$, $\bar{\beta}$ are volumes of information in the request and response to the request; γ_1, γ_2 are throughputs of communication channels “center-node” and “node-post”; h_1, h_2 are the processing speeds of the request and response in the network nodes.

As an indicator of the reliability of the network $k_2(S)$, we use the coefficient of its readiness:

$$k_2(s) = \delta^C \times \left(\delta^U\right)^u \times \left(\delta^E\right)^n \times \\ \times \left(\delta^{CU}\right)^u \times \left(\delta^{UE}\right)^n \rightarrow \max_{s \in S^*}, \qquad (20)$$

where: δ^C, δ^U, δ^E, δ^{CU}, δ^{UE} – are readiness factors of the center, node, post, communication channels “center-node” and “node-element”;

n, $u = \sum\limits_{i=1}^{n} s_{ii}$ are the count of elements and nodes in the network.

To assess the survivability $k_3(s)$, we use the value of a part of the posts associated with the center in a workable network with single damage to its components. At the same time, it is known that, regardless of the type of network structure, in case of damage to the center – $k_3(s) \equiv 0$, and in case of damage to one element or one communication channel “node-pos” $k_3(s) \equiv (n-1)/n$ [8].

The criterion for maximizing network survivability will take into accounts only damage to the links “center-node”, “node-post” and nodes:

$$k_3(s) = \left\{ \min_{1 \le j \le n} \left[\left(n - \sum_{j=2}^{n}\sum_{i=j}^{n} s_{ji} s_{ii} \right) / n \right] \right\} \rightarrow \max_{s \in S^*}. \qquad (21)$$

The objective function of minimizing the reduced costs for reengineering the topological structure of the network in the above notation will have the following form:

$$k_4(s', s) = \sum_{i=1}^{n} [c_i (1 - s'_{ii}) s_{ii} + d_i s'_{ii} s_{ii}] + \\ + \sum_{j=1}^{n}\sum_{i=j}^{n} [c_{ij} (1 - s'_{ij}) s_{ij} + d_{ij} s'_{ij} s_{ij}] \rightarrow \min_{s \in S^*}. \qquad (22)$$

To estimate the costs of reengineering networks with quasi-uniform placement of control posts across the territory, a modified Nocker model (R. Nocker) can be used. It contains analytical estimates of the optimal number of nodes and costs for networks with radial node structures [19].

Exact combinatorial methods for solving problems of reengineering of topological structures have non-polynomial time complexity, which involves the generation and analysis of huge sets of feasible options. After formalizing the goals of reengineering in the form of explicit functions (19)-(22), it is required to reduce the set of feasible reengineering options to a subset of effective options $S^E \subseteq S^*$.

MODELS AND METHODS FOR THE FORMATION OF EFFECTIVE OPTIONS FOR REENGINEERING

The task of identifying a subset of effective options for network S^E reengineering is to exclude from the set of feasible options S^*, a subset of dominated (non-optimal) options S^S [18]. The variant of reengineering of the monitoring network will be called effective $s^E \in S^*$ if on the set of admissible S^* there is no variant of another variant $s \in S^*$, for which the inequalities would be satisfied [12]:

$$k_j(s) \geq k_j(s^E), \text{ if } k_j(s) \to max, \qquad (23)$$

$$k_j(s) \leq k_j(s^E), \text{ if } k_j(s) \to min, \qquad (24)$$

and at least one of them was strict.

At the same time, it is known that for the problems of designing and reengineering of centralized radial-nodal structures $\left|S^E\right| << \left|S^*\right|$ [18].

If parallel generate and screening out of inefficient variants by the method of pairwise comparisons is impossible, methods based on the Karlin and Germeier theorems can be used to solve this problem.

Using a method based on Karlin's theorem, a subset of effective network S^E reengineering options can only be determined on a convex set of feasible options S^*.

It is found by combining options s_j^o, $j = \overline{1,m}$, corresponding to the optimum for each of the local criteria $k_j(s)$.

Such options are determined by solving a mathematical programming problem with respect to parameters [18]:

$$\lambda_j \in \Lambda = \{\lambda_j : \lambda_j > 0 \ \forall j = \overline{1,m}, \ \sum_{j=1}^{m} \lambda_j = 1\}, \qquad (25)$$

$$s_j^o = arg \max_{s \in S^*} \{P(s) = \sum_{j=1}^{m} \lambda_j \xi_j(s)\}, \qquad (26)$$

where $\xi_j(s)$, $j = \overline{1,m}$ are values of the linear utility function of the i -th local criterion (13).

The method based on the Germeier theorem allows us to determine a subset of efficient options S^E not only on a convex, but also on a non-convex set of feasible options S^*. The subset is determined by the union of the variants s_j^o, $j = \overline{1,m}$, maximizing the minima with respect to each of the local criteria $k_j(s)$. Such options are determined by solving a mathematical programming problem with respect to parameters [18]:

$$\lambda_j \in \Lambda = \{\lambda_j : \lambda_j > 0 \ \forall j = \overline{1,m}, \ \sum_{j=1}^{m} \lambda_j = 1\}, \qquad (27)$$

$$s_j^o = arg \max_{s \in S^*} \{P(s) = \min_j \lambda_j \xi_j(s)\}. \qquad (28)$$

It is not possible to single out the entire set of efficient alternatives $S^E \subseteq S$ using methods based on the Karlin and Germeier theorems due to the difficulties in solving parametric programming problems (25)-(28). In the procedures for reengineering networks of extra-large dimension, evolutionary methods based on genetic algorithms can be used to determine Pareto fronts [20, 21], [22, 23], [24, 25]. They do not guarantee selection of complete subsets of efficient options, but they allow one to find a compromise between the accuracy of solutions and the cost of computer time for finding solutions.

To reduce the time for solving problems, it is proposed to integrate the procedure for screening out inefficient options directly into the methods used to optimize the topological structures of networks. This allows you to significantly reduce the cost of computer time and memory (Table 1).

The results of the study of the method of pairwise comparisons, its modifications, methods based on the Karlin and Germeier theorems in solve problems of selecting subsets of effective options are given in [18].

MODELS AND METHOD OF SCALAR MULTICRITERIA ESTIMATION OF REENGINEERING OPTIONS

In view of the incomplete certainty of the requirements for the properties of options for reengineering the monitoring network, it is proposed to use the function of belonging to a fuzzy set “the best reengineering option” as a function of overall utility [26, 27]. In this case, the fuzzy set “the best reengineering option” can be represented as a set of ordered pairs.

In view of the incomplete certainty of the requirements for the properties of options for reengineering the monitoring network, it is proposed to use the function of belonging to a fuzzy set “the best reengineering option” as a function of overall

Table 1. **Average cardinalities of subsets of efficient solutions S^E depending on the number of criteria m and the size of the set of feasible options $S*$**

m	The size of the set of feasible options for build a network $S*$									
	10000	20000	30000	40000	50000	60000	70000	80000	90000	100000
2	8	9	10	11	12	13	16	19	22	26
3	33	37	42	56	59	63	65	69	74	77
4	151	159	164	253	292	297	292	302	329	342
5	401	501	752	591	785	791	941	1147	975	1034
6	827	1309	1394	1587	1750	2116	2237	2274	2398	2450
7	1749	2572	3010	3284	3732	4071	4741	4942	5235	5391

Source: compiled by the authors

utility $P(s)$ [26, 27]. In this case, the fuzzy set "the best reengineering option" can be represented as a set of ordered pairs:

$$\begin{aligned}&«Re\,engineering \quad best \quad option» = \\ &=\{<s,P(s)>\},\end{aligned} \qquad (29)$$

where: $s \in S*$ is monitoring network reengineering option; $P(s)$ it is a function that determines the degree of belonging of the option s to the fuzzy set "the best reengineering option".

Membership functions of the form (13) are most widely used in practice. The disadvantage of such models is that they allow almost unlimited compensation of some properties of the solution by others. As a model for scalar multicriteria estimation, it is proposed to use a function based on the Kolmogorov-Gabor polynomial [16, 19], [26, 27]:

$$\begin{aligned}&P(s)=\sum_{j=1}^{m}\lambda_i \cdot \xi_i(s)+\sum_{j=1}^{m}\sum_{l=j}^{m}\lambda_{jl}\cdot \xi_j(s)\cdot \xi_l(s)+\\ &+\sum_{j=1}^{m}\sum_{l=j}^{m}\sum_{k=l}^{m}\lambda_j(s)\cdot \xi_l(s)\cdot\xi_k(s)+...,\end{aligned} \qquad (30)$$

where λ_j, λ_{jl}, λ_{jlk} are weight coefficients of local criteria $k_j(s)$ and their products $\lambda_j \ge 0$, $\lambda_{jl} \ge 0$, $\lambda_{jlk} \ge 0$, $j,l,k=\overline{1,m}$.

Model (30) is universal and allows describe all possible preferences of the decision maker, given by the values of the parameters $\lambda_j \ge 0$, $\lambda_{jl} \ge 0$, $\lambda_{jlk} \ge 0$, $j,l,k=\overline{1,m}$. Its particular case is the popular additive model (12).

By introducing the notation:

$$\begin{aligned}&\xi_1(s)\cdot \xi_1(s)=\xi_{m+1}(s),\ \lambda_{1,1}=\lambda_{m+1},\\ &\xi_1(s)\cdot \xi_2(s)=\xi_{m+2}(s),\ \lambda_{1,2}=\lambda_{m+2},\ \dots\end{aligned} \qquad (31)$$

model (30) may be represented in additive form with respect to the parameters $\lambda_j \ge 0$, $\lambda_{jl} \ge 0$, $\lambda_{jlk} \ge 0$, $j,l,k=\overline{1,m}$:

$$P(s)=\sum_{j=1}^{M}\lambda_j\,\xi_j(s), \qquad (32)$$

where M is a count of parameters λ_j, λ_{jl}, λ_{jlk},....

The function of utility of the values of local criteria $k_j(s)$ б $j=\overline{1,m}$ must satisfy the following requirements [18]: be dimensionless; be monotonous; have an interval of change from 0 to 1; be invariant to the form of the extremum of local criteria; implement linear and non-linear dependences on the values of the local criterion.

$k_i(s)$, $i=\overline{1,m}$.

The disadvantage of function (13) is the impossibility of implementing Z- and S-shaped dependencies on the values of the local criterion. Z- and S-shaped dependencies more adequately display the estimates of design solutions. If we introduce the notation $\bar{k}(s)=\bar{k}_j(s)=\xi_j(s)$ in (13) at $\eta_j=1$, $j=\overline{1,m}$ then such dependencies allow us to implement models based on [26]:

– Gaussian function

$$\xi(s)=exp\left[-\frac{(\bar{k}(s)-1)^2}{c}\right],\quad c>0; \qquad (33)$$

– logistic function:

$$\xi(s)=\frac{1}{1+exp\left[-\dfrac{(\bar{k}(s)-a)}{b}\right]}, \qquad (34)$$

where: a – abscissa of the inflection point; b is a parameter that determines the type of dependence;

– Harrington function:

$$\xi(s)=exp\left\{-exp\left[(g\cdot\bar{k}(s)-a)\right]\right\}, \qquad (35)$$

where g is a non-linear parameter; a / g are the relation, which is defined the inflection point of the function;

– modified Gaussian function:

$$\xi(x)=exp\left[-\frac{(\bar{k}(x)-1)^{2\cdot\alpha}}{c}\right], \qquad (36)$$

where $c>0$, α parameters that determine the type of dependence;

– gluing functions of power functions (13):

$$\xi(s)=\begin{cases}\bar{a}\cdot\left(\dfrac{\bar{k}(s)}{\bar{k}_a}\right)^{\alpha_1}, \quad 0\le\bar{k}(s)\le\bar{k}_a; \\ \bar{a}+(1-\bar{a})\cdot\left(\dfrac{\bar{k}(s)-\bar{k}_a}{1-\bar{k}_a}\right)^{\alpha_2}, \\ \bar{k}_a<\bar{k}(s)\le 1,\end{cases} \qquad (37)$$

where: $\bar{k}_a$, $\bar{a}$ are the values of the coordinates of the gluing point of the function, $0\le\bar{k}_a\le 1$, $0\le\bar{a}\le 1$; $\alpha_{1i,}\alpha_{2i}$ – parameters that determine the type of dependence on the initial and final segments of the function;

– gluing power functions:

$$\xi(s)=\begin{cases}2^{p-1}\cdot\left[\bar{k}(s)\right]^p, \quad 0\le\bar{k}(s)\le 0.5; \\ 1-2^{p-1}\cdot\left[\dfrac{0.5-\bar{k}(s)}{0.5}\right]^p, \\ 0.5<\bar{k}(s)\le 1,\end{cases} \qquad (38)$$

where p – a parameter that defines a specific type of dependency.

For the most accurate non-linear (including S- and Z-shaped) approximation of estimates of the values of local criteria, it is proposed to use the universal value function [26, 27]:

$$\xi(s)=\begin{cases}\bar{a}(b_1+1)\left(1-\left(b_1\Big/\left(b_1+\dfrac{\bar{k}(s)}{\bar{k}_a}\right)\right)\right), \\ 0\le\bar{k}(s)\le\bar{k}_a; \\ \bar{a}+(1-\bar{a})(b_2+1)\times \\ \times\left(1-\left(b_2\Big/\left(b_2+\dfrac{\bar{k}(s)-\bar{k}_a}{1-\bar{k}_a}\right)\right)\right), \\ \bar{k}_a<\bar{k}(s)\le 1,\end{cases} \qquad (39)$$

where: $\bar{k}(s)=\xi_j(s)$, $j=\overline{1,m}$; $\bar{k}_a,\bar{a}$ – gluing point coordinates, $0\le\bar{k}_a\le 1$, $0\le\bar{a}\le 1$; b_1,b_2– coefficients that determine the type of dependence on the initial and final segments.

Model (37) has the highest accuracy in representing the preferences of the decision maker, and model (39) has the best value of the complex indicator “accuracy-complexity” for calculating its values among known nonlinear functions [25, 26].

The complexity of scalar multicriteria estimation models (12) and (30) can be reduced by reducing the number of objective functions based on the principal component method [24]. The essence of the method is that if two objective functions built on the basis of local criteria $k_j(s)\rightarrow\underset{s\in S^*}{extr}$ and $k_l(s)\rightarrow\underset{s\in S^*}{extr}$, they have a negative value of the correlation function, then they are in conflict and are included in the data matrix for analyzing the Pareto front. Based on the results of the analysis of the eigenvectors of the correlation matrix, the least informative local criteria are excluded from the estimation model. Despite the reduction in the complexity of the multicriteria evaluation procedure, this method does not guarantee the save of the dominance structure.

MODEL AND METHOD FOR SOLVING THE PROBLEM OF PARAMETRIC SYNTHESIS OF THE FUNCTION OF SCALAR MULTICRITERIA ESTIMATION

To apply the scalar multicriteria estimation models (12) and (30) in the tasks of reengineering monitoring networks, it is first necessary to select the values of their parameters λ_j, $j=\overline{1,m}$ or λ_j, λ_{jl}, λ_{jlk}, which best correspond to the preferences of the decision maker. Traditionally, such a task is solved by expert methods of ranking, hierarchy analysis, sequential preferences, including AHP, TOPSIS, VIKOR, COPRAS, MULTIMOORA, PROMETHEE, GAIA [29, 30], [31, 32], [33, 34]. The disadvantage of these methods, despite their widespread use, is the complexity of the examination, the relatively low accuracy of estimates due to the frequent inconsistency of experts' preferences.

As an alternative to traditional methods of expert estimation of parameters, it is proposed to use technology based on the method of comparator identification [18, 26], [27].

The task of parametric synthesis of the model of multicriteria evaluation of reengineering options will be solved using the universal utility function

(30), built on the basis of the universal utility function of local criteria (39).

In the process of examination, the decision maker analyzes pairs of network reengineering options from a subset of effective ones $s^E \in S^*$ according to a set of local criteria $k_j(s),\ j=\overline{1,m}$. Based on the results of the analysis, a binary strict preference relation is formed, which establishes the relative value of reengineering options:

$$R(S^E)=\{<s,v>:\ s,v \in S^E,\ s \succ v\}. \qquad (40)$$

Using relations (10) for the formed strict preference relation (4), we compose a set of inequalities of the form:

$$P(s,\lambda) > P(v,\lambda),\ s,v \in R(S^E), \qquad (41)$$

where $\lambda=[\lambda_j]_{j=1}^N$ – desired vector of model parameters (30).

The task of parametric synthesis of the model is to determine the vector λ that satisfies the formed set of inequalities (41), as well as the condition of vector normalizing:

$$\begin{cases} \eta_j(\lambda) \equiv \sum\limits_{j=1}^N \lambda_j\,\xi_j(s) > \sum\limits_{j=1}^N \lambda_j\,\xi_j(v), \\ s,v \in R(S^E);\ j=\overline{1,L}; \\ \eta_{L+1}(\lambda) \equiv \sum\limits_{j=1}^N \lambda_j = 1,\ \lambda_j \ge 0,\ i=\overline{1,N}, \end{cases} \qquad (42)$$

where $L=\left|S^E\right|$ – the power of the binary strict preference relation (40).

At the same time, if preference (40) is consistent, system (42) can have an infinite number of solutions.

One of the ways to solve such systems is to search for the Chebyshev point [16, 19], [35]. It allows you to reduce the original problem to a linear programming task. To do this, an additional variable λ_{N+1} and constraint $\eta_j(\lambda) \le \lambda_{N+1},\quad j=\overline{1,L}$ are introduced into system (42). Then finding the Chebyshev point of the set of inequalities (42) reduces to a linear programming problem:

$$\begin{cases} -\eta_i(\lambda)+\lambda_{N+1} \ge 0, \quad i=\overline{1,L}; \\ \eta_{L+1}(\lambda) \equiv \sum\limits_{j=1}^N \lambda_j = 1,\ \lambda_j \ge 0; \\ \lambda_{N+1} \to min. \end{cases} \qquad (43)$$

If the binary relation (40) is consistent, then the system of inequalities (41) will be compatible. In such cases $r=\min\limits_{\lambda}\max\limits_{j}\eta_j(\lambda) \le 0$, and the resulting set of parameters $\lambda=[\lambda_j]_{j=1}^N$ will be maximally resistant to possible changes in the preferences of the decision maker.

Consider an example of solving problem (42) of parametric synthesis of a scalar multicriteria estimation function on a set of 12 effective options for building a monitoring network S^E. Estimates of the functional and cost properties of the network are normalized and represented as the values of the utility functions of local criteria $\xi_j(s)\ j=\overline{1,4}$ (Table 2).

Based on the results of the analysis of network reengineering options, the decision maker formed a binary strict preference relation of the form $R(S^E)$ (40), which establishes the following order:

$$s_1 \succ s_2 \succ s_3 \succ \ldots \succ s_{12} \qquad (44)$$

Find the Chebyshev point of the system of inequalities (42) by solving the linear programming problem (43). Its solution will be the vector of the best values of the model parameters:

$$\lambda=[0{,}253;0.252;0.244;0.251]^T.$$

The values of the general utility $P(s)$ function corresponding to it (Table 2) completely restore the order given by the decision maker on the set of options for build the network (44).

CONCLUSIONS

The analysis of the modern state of the problem of reengineering the topological structures of terrestrial ecological monitoring networks is carried out and the relevance of improving the universal mathematical models of multicriteria problems is shown.

Within the framework of the aggregative-decompositional approach to solving the problem, it is divided into a set of tasks, considering their interrelationships in terms of input and output data. This made it possible to define many tasks that form the basis of network reengineering procedures.

To improve the efficiency of technologies for automated design of ecological monitoring networks, a set of models is proposed, including: a systemological model of iterative technology for obtaining a design solution; analytical models for evaluating the properties of network reengineering options in terms of efficiency, reliability, survivability and costs; models for the formation of effective options for reengineering; models of scalar multicriteria estimation of network reengineering options based on utility theory; model of the task of parametric synthesis of the function of scalar multicriteria estimation.

Table 2. **Characteristics of build network options**

s	$\xi_1(s)$	$\xi_2(s)$	$\xi_3(s)$	$\xi_4(s)$	$P(s)$	s	$\xi_1(s)$	$\xi_2(s)$	$\xi_3(s)$	$\xi_4(s)$	$P(s)$
s_1	0.851	0.974	0.595	0.978	0.851	s_7	0.799	0.915	0.902	0.435	0.762
s_2	0.926	0.707	0.791	0.943	0.842	S_8	0.984	0.525	0.351	0.815	0.671
s_3	0.958	0.701	0.787	0.878	0.831	s_9	0.519	0.938	0.695	0.497	0.662
s_4	0.972	0.886	0.845	0.593	0.824	s_{10}	0.892	0.062	0.819	0.851	0.655
s_5	0.651	0.862	0.789	0.965	0.817	s_{11}	0.989	0.345	0.306	0.632	0.570
s_6	0.458	0.834	0.975	0.817	0.769	s_{12}	0.981	0.767	0.275	0.216	0.563

Source: compiled by the authors

Their implementation will be able to increase the degree of automation of network reengineering processes, reduce the time for solving the problem of multicriteria choice due to the reduction in the time complexity of the analysis procedures, and increase the stability of the decisions made by compromising their choice only from a subset of effective ones.

The results obtained can be used in the procedures for making multicriteria decisions in automation systems for the design of monitoring networks, corporate computer networks, and other geographically distributed objects. The direction of further research in this area may be the uncertainty of input data in models, the functional and cost characteristics of network equipment and the preferences of decision makers using interval or fuzzy analysis tools.

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Математичні моделі багатокритеріальної задачі реінжинірингу топологічних структур мереж екологічного моніторингу

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АНОТАЦІЯ

У статті розглядаються теоретичні аспекти проблеми реінжинірингу топологічних структур наземних мереж екологічного моніторингу. За результатами аналізу сучасного стану проблеми виявлено, що необхідність зміни мережі точок контролю, підвищення вимог до оперативності та точності спостережень, поява більш досконалих технологій збору, обробки, зберігання та передачі інформації на певному етапі вимагають проведення реінжинірингу існуючих мереж. Це вимагає вдосконалення технологій системної оптимізації мереж та їхнього математичного забезпечення в частині врахування особливостей проблеми реінжинірингу, а також використовуваних для цього математичних моделей та методів. Для вирішення проблеми реінжинірингу мереж запропоновано агрегативно-декомпозиційний підхід, виконано її розбиття на множину задач з урахуванням їх взаємозв'язків за вхідними та вихідними даними. Це дозволило визначити множину задач, що становлять основу процедур реінжинірингу мереж. Для підвищення ефективності технологій автоматизованого проектування та реінжинірингу наземних мереж екологічного моніторингу запропоновано комплекс математичних моделей, що охоплюють основні етапи їх життєвих циклів: системологічну модель ітераційної технології отримання проєктних рішень; аналітичні моделі оцінки властивостей варіантів реінжинірингу мереж за показниками оперативності, надійності, живучості та витрат; моделі виділення ефективних варіантів реінжинірингу мереж на основі теорем Карліна та Гермейєра; модель оцінки локальних властивостей варіантів у вигляді функції корисності локальних критеріїв, що дозволяє реалізувати як лінійні, так і нелінійні (включаючи Z- та S-подібні) залежності від їх значень; модель скалярного багатокритеріального оцінювання варіантів реінжинірингу мереж на основі теорії корисності Для практичної реалізації моделей багатокритеріальних задач реінжинірингу топологічних структур мереж запропоновано використовувати метод паралельного з генерацією формування ефективних проектних рішень та метод компараторного параметричного синтезу функції скалярного багатокритеріального оцінювання. Працездатність та ефективність запропонованих математичних моделей та методів продемонстрована на прикладах розв’язання задач виділення підмножин Парето-оптимальних варіантів побудови мереж і параметричного синтезу функції скалярного багатокритеріального оцінювання. Застосування на практиці запропонованого комплексу моделей та методів дозволить підвищити ступінь автоматизації процесів реінжинірингу мереж, скоротити час вирішення задачі багатокритеріального вибору завдяки зниженню тимчасової складності процедур аналізу та підвищити стійкість прийнятих рішень за рахунок компромісного їх вибору лише з підмножини ефективних.

Ключові слова: мережа екологічного моніторингу; технологія проектування; реінжиніринг; прийняття рішень; багатокритеріальна оптимізація

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