Формалізація задачі реінжинірингу топологічних структур наземних мереж екологічного моніторингу

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Анотація

Зміна вимог, умов експлуатації, розвиток технічних засобів і технологій на певному етапі призводять до необхідності проведення реінжинірингу існуючих систем екологічного моніторингу. Для забезпечення ефективності проектних рішень запропоновано спільне розв’язання задач структурної, топологічної параметричної та технологічної оптимізації мереж системи за множиною показників якості. Визначена базова постановка задачі реінжинірингу топологічних структур централізованих трирівневих наземних мереж, для якої формалізовані множина допустимих рішень і оцінки показників витрат, оперативності, надійності та живучості. Запропоновані універсальні функції для скалярного оцінювання варіантів точніше описують переваги особи, що приймає рішення, і дозволяють скоротити часову складність процедур оцінювання.

Ключові слова

Мережа екологічного моніторингу, структура, топологія, реінжиніринг, багатокритеріальна оптимізація.

Formalization of the reengineering problem of ground-based environmental monitoring networks topological structures

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Abstract

Changes in requirements, operating conditions, development of technical means and technologies at a certain stage lead to the need for reengineering of existing environmental monitoring systems. To ensure the effectiveness of design solutions, it is proposed to jointly solve the problems of structural, topological, parametric and technological optimization of system networks in terms of a variety of indicators. The basic formulation of the problem of reengineering of the topological structures of centralized three-level ground networks has been determined, for which a set of feasible solutions and estimates of indicators of costs, efficiency, reliability and survivability are formalized. The proposed universal functions for scalar estimation of options more accurately describe the preferences of the decision-maker and reduce the time complexity of the estimation procedures.

Keywords

Environmental monitoring network, structure, topology, reengineering, multi criteria optimization.

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1. Introduction

The safe development of a modern technogenic society requires systematic observations, control, assessment of human impact on the environment, carried out by the systems of integrated environmental monitoring [1]. One of the main functions of such systems is the receipt, registration and timely transmission of large time series of data for the analysis [2-3]. Data transmission in monitoring systems is carried out using networks with different structures depending on the characteristics of the objects of control. The improvement of technologies for collecting, transmitting and processing data opens up new prospects for the development of monitoring networks: inexpensive data loggers are increasingly used [4]; due to the numerous advantages of automated measurements, data are collected continuously with minimal human intervention [5]; real-time data collection plays an important role in weather forecasting, hydrological analysis, disaster impact assessment, etc. [6].

Changes in operating conditions (requirements for reliability, efficiency and accuracy of observations, the number of objects of observation) or monitoring tools (improvement of technologies for processing, storing and transmitting information) reduces the effectiveness of existing options for implementing networks and requires their reengineering. The process of monitoring networks reengineering is carried out based on the results of solving a complex of combinatorial problems of optimizing their structures, topologies, parameters of elements and channels of information transmission, selection of technologies for collecting, transmitting and processing information [7].

Taking into account the fact that the cardinalities of the sets of admissible functioning technologies, parameters of elements and connections of networks are insignificant, the main difficulties are in solving problems of optimizing their topological structures. Such problems are solved with a variety of functional and cost indicators, taking into account numerous restrictions. This requires the use of modern models and methods to support the adoption of multi-criteria decisions [8-9].

Despite numerous publications devoted to solving the problems of reengineering the topological structures of ground-based environmental monitoring networks, a contradiction was revealed between the need to increase the efficiency of existing options for their implementation and the limitations of mathematical models of multi criteria problems of their optimization. In particular, it is necessary to improve the adequacy of models for assessing functional and expenditure indicators, preferences, decision-makers, and scalar multi-criteria assessment models for building networks [10-11].

The aim of the study is to increase the efficiency of technologies for computer-aided design of ground-based environmental monitoring networks through the development of mathematical models of multi criteria problems of reengineering of their topological structures.

2. Mathematical model of the basic problem of network reengineering

As the scale of monitoring systems grows, their cost and functional characteristics become more and more dependent on the topology of the (territorial) organization. As a result, it becomes necessary to solve topological optimization problems together with traditional problems of structural synthesis. This gives rise to the problem of structural-functional-parametric and topological synthesis. As a result of decomposition of the problem for the reengineering of ground-based environmental monitoring networks as territorially distributed objects at the lower level, the following tasks are identified [7]:

- determination of the network construction principles;
- choice of network structure;
- determination of topology of elements (nodes, center) and channels of the network;
- choice of the network functioning technology;
- determination of parameters of elements (nodes, center) and channels of the network;
- evaluation of efficiency and selection of design solutions.

After choosing the principles of construction and the technology of functioning, the task of reengineering the topological structures of three-level centralized monitoring networks is considered in this formulation [12]. Specified: a set of elements of the existing network $I=\{i\}$,

$i=\overline{1,n}$, which cover the entire set of monitoring objects; the existing version of the topological structure $s' \in S$ (where S is the set of admissible options), which is given by the locations of elements, nodes, center (the center is located at the base of the element $i = 1$), as well as links between elements, nodes and the center $[s'_{ij}]$, $i,j=\overline{1,n}$ (where $s'_{ij}=1$, if there is a direct connection between elements i and j- and $s'_{ij}=0$ otherwise); the cost of creating or upgrading nodes $[c_i]$, $[d_i]$, $i=\overline{1,n}$ and links $[c_{ij}]$, $[d_{ij}]$ $i=\overline{1,n}$.

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

The set of acceptable options for building a centralized three-level network is set by the conditions:

$$S=\{s\}=\begin{cases} [s_{ij}], s_{ij}\in\{0,1\},\ i,j=\overline{1,n},\ s_{11}=1; \\ \sum\limits_{i=j}^{n} s_{ij} \geq 1\ \forall j=\overline{1,n}; \\ \sum\limits_{j=1}^{n}\sum\limits_{i=j}^{n} s_{ij} = n+\sum\limits_{i=1}^{n} s_{ii}, \\ s_{ii}=1 \rightarrow s_{i1}=1\ \forall i=\overline{1,n}; \\ s_{ii}\wedge s_{ij}=1 \rightarrow ij=\arg\min\limits_{1\leq i,j\leq n} c_{ij}\ \forall i,j=\overline{1,n}. \end{cases} \tag{1}$$

Each of the network reengineering options is set by the number of nodes *u*, in it, their locations and the scheme of connections between elements, nodes and the center $[s_{ij}]$, $i,j=\overline{1,n}$. It is considered that: the entire set of monitoring objects is controlled with a given frequency; nodes of the network are placed exclusively on the basis of elements; the elements are connected to the nodes in terms of the minimum cost (distance), the volume of requests to each element of the network is equal to $\alpha=[\alpha_i],\ \alpha_i=const,\ i=\overline{1,n}$; the volume of responses from each of the elements is equal to $\beta=[\beta_i],\ \beta_i=const,\ i=\overline{1,n}$.

Let us simplify the target function of the costs of network reengineering [12]: the costs of dismantling nodes and channels of the existing structure and the cost of resources that can be reused after dismantling the equipment will be taken into account in the costs of nodes and channels of the new network. Using the designations introduced above, we represent the target cost function in the following form:

$$\begin{aligned} k_1(s',s) &= \sum_{i=1}^{n}[c_i(1-s'_{ii})s_{ii}+d_i s'_{ii}s_{ii}]+ \\ &+\sum_{j=1}^{n}\sum_{i=j}^{n}[c_{ij}(1-s'_{ij})s_{ij}+d_{ij}s'_{ij}s_{ij}] \rightarrow \min_{s\in S}. \end{aligned} \tag{2}$$

The criterion of efficiency, which corresponds to minimizing the maximum time for obtaining monitoring data, can be presented in the following form:

$$k_2(S)=\left\{\tau^C+\frac{\overline{\alpha}}{\gamma_1}+\tau^E+\frac{\overline{\beta}}{\gamma_2}+\left(\frac{\overline{\alpha}}{\gamma_1}+\frac{\overline{\alpha}}{h_1}+\frac{\overline{\beta}}{h_2}+\frac{\overline{\beta}}{\gamma_2}\right)\sum_{j=1}^{n}\sum_{l=j}^{n}s_{jl}s_{jj}\right\}\rightarrow \min_{s\in S}, \tag{3}$$

where τ^C, τ^E is the time for the center to issue a request and receive information on the monitoring object by the element; $\overline{\alpha}$, $\overline{\beta}$ is the amount of information in the request and the response to the request; γ_1, γ_2 are capacities of communication channels "center-node" and "node-element"; h_1, h_2 is speed of request and response processing in network nodes.

We use the coefficient of the network availability as an indicator of its reliability,

$$k_3(s) = \delta^C \times \left(\delta^U\right)^u \times \left(\delta^E\right)^n \times$$
$$\times\left(\delta^{CU}\right)^u \times \left(\delta^{UE}\right)^n \to \max_{s\in S} , \qquad (4)$$

where δ^C, δ^U, δ^E, δ^{CU}, δ^{UE} are availability factors of the center, node, element, communication channels "center-node" and "node-element"; n, $u = \sum_{i=1}^{n} s_{ii}$ is the number of elements and nodes in the network.

We use the value of the proportion of elements connected to the center in an operable network with single damage to its components as an indicator of survivability $k_4(s)$. In this case, regardless of the type of network structure, when the center is damaged $k_4(s) \equiv 0$, and when one element or one communication channel "node-element" is damaged $k_4(s) \equiv (n-1)/n$.With this in mind, the criterion of maximizing the survivability of the network will take into account only the damage of the connections "center-node", "node-element" and nodes:

$$k_4(s) = \left\{ \min_{1\le j\le n} \left[\left(n - \sum_{j=2}^{n}\sum_{i=j}^{n} s_{ji}s_{ii} \right) / n \right] \right\} \to \max_{s\in S} . \ (5)$$

A huge number of options is generated and analyzed for a set of indicators (2)-(5) in the process of network optimization. Scalar multifactor assessment models are used to select a subset of the most effective options and the best among them for building an environmental monitoring network [8-11].

3. Scalar evaluation of network construction options

To determine the scalar estimates of the quality of variants, we use the apparatus of utility theory [15]. For decision options, we will set the meaning of their value $P(s)$,, which will determine their order by quality. Wherein $\forall s,v \in S$:

- $s \sim v \leftrightarrow P(s) = P(v)$;
- $s \succ v \leftrightarrow P(s) > P(v)$;
- $s \succsim v \leftrightarrow P(s) \ge P(v)$.

It is proposed to establish the value of scalar estimates for the quality of options based on the generalized utility function built on the basis of the Kolmogorov-Gabor polynomial [10-11, 15]:

$$P(s) = \sum_{i=1}^{4}\lambda_i\xi_i(s) + \sum_{i=1}^{4}\sum_{j=i}^{4}\lambda_{ij}\xi_i(s)\xi_j(s) + \sum_{i=1}^{4}\sum_{j=i}^{4}\sum_{l=j}^{4}\lambda_{ijl}\xi_i(s)\xi_j(s)\xi_l(s) + \dots , \qquad (6)$$

$$\xi_i(s) = \begin{cases} \bar{a}_i \cdot (b_{i1}+1) \cdot \left\{ 1 - \left[b_{i1} / \left(b_{i1} + \dfrac{\bar{k}_i(s)}{\bar{k}_{ia}} \right) \right] \right\}, 0 \le \bar{k}_i(s) \le \bar{k}_{ia}; \\ \bar{a}_i + (1-\bar{a}_i)\cdot(b_{i2}+1) \left\{ 1 - \left[b_{i2} / \left(b_{i2} + \dfrac{\bar{k}_i(s) - \bar{k}_{ia}}{1-\bar{k}_{ia}} \right) \right] \right\}, \bar{k}_{ia} < \bar{k}_i(s) \le 1, \end{cases} \qquad (7)$$

where λ_i, λ_{ij}, λ_{ijl}, are coefficients of importance of $k_i(s)$, $i=\overline{1,4}$ criteria and products of criteria $k_i(s)$, $k_j(s)$, $k_l(s)$; $\xi_i(s)$ is the value of the utility function of the partial criterion $k_i(s)$, $i=\overline{1,4}$ for the option $s \in S$; $\bar{k}_{ia}, \bar{a}_i$ is the value of the coordinates of the point of sewing the function (7); $0 \le \bar{k}_{ia} \le 1$, $0 \le \bar{a}_i \le 1$; b_{i1}, b_{i2} are parameters that determine the nature of function (7) on the initial and final segments.

The generalized utility function (6) makes it possible to describe any consistent advantages of the decision maker. Function (7) is the best in terms of the "accuracy-complexity" complex indicator among the common utility functions of particular criteria [10].

4. Conclusions

Based on the results of the analysis of the current state of the problem, it was found that changes in requirements, operating conditions, the development of technical means and information technologies lead to the need for reengineering of existing environmental monitoring networks. To ensure the effectiveness of design solutions, it is advisable to solve jointly combinatorial problems of structural and topological optimization of networks with a variety of functional and cost indicators. Mathematical relationships were obtained to assess options for building centralized three-level networks in terms of costs, efficiency, reliability and survivability. Their use makes it possible to carry out scalar evaluations of alternative options in automatic mode. The proposed options evaluation functions more accurately describe the benefits of the design decision maker and allow reducing the time complexity of the evaluation procedures. The direction of further research can consist in accounting of the uncertainty of the functional and cost characteristics of networks in models of the problem using the apparatus of fuzzy or interval analysis and the decoupling of effective methods for optimizing networks with a variety of indicators.

5. References

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