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REENGINEERING THE TOPOLOGICAL STRUCTURES OF LARGE-SCALE MONITORING SYSTEMS

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Abstract. As part of the solution of problem optimization of large-scale facilities carried out formalization of the system description of large-scale monitoring, defined the composition and the relationship subsets of elements, relationships, topologies and properties. Formulated the mathematical model and the task of reengineering topological structures of centralized three-tier system of large-scale monitoring based on indices of cost and efficiency. The proposed mathematical model explicitly set relation between costs for the reengineering and time processing messages in the system from its structure and topology. The analysis of the objective function revealed that envelopes their local extrema are one-extreme (relative to the number of nodes in the system). Considering this, proposed a method of directed inspection of local extrema, which allow to find best solutions in terms of the minimum additional cost. Selection of the single solution from a set of effective proposed to carry out the method of hierarchy analysis or cardinalist approach aided by the additive function of general utility. The values of the weighting coefficients of the utility functions is carried out by an expert or based on comparator identification.

Practical application these results allows reduce the time of obtaining solutions and more accurate solving of large dimension problem.

Key words: large-scale monitoring system (LSMS), structure, topology, reengineering.

INTRODUCTION

In modern conditions, a lot of scientific and research, social and economic, as well as technical decisions are based on the data provided by large-scale monitoring systems (LSMSs). This is exemplified by the systems of astronomic, ecological, radiation, geological and hydrometeorological, economic and medical monitoring.

Changes of the monitoring conditions (emerging new objects of observation, stricter requirements to the operativeness and accuracy of observations) and (or) new tools (appliances and technologies) lead to inefficiency of the current variant of the system construction. Any attempts to adapt the system do not secure the best outcome.

The most effective variant of the system construction can be obtained through its reengineering, which suggests a fundamental reconsideration of the current state of the observed objects, the entire system, tools and technologies of monitoring, as well as through its radical redesign.

The notion “reengineering” was suggested and originally interpreted in the study [1] that revealed reengineering principles for business processes of companies. Most contemporary publications on various aspects of reengineering problem also refer to reengineering business processes or software structures, and use the notion of “reengineering” alongside such notions as “redesign”, “evolution”, “migration”, “modernization”, and “restructuring” [2–5].

In LSMSs, operativeness and cost indices largely depend on the applied technology, structure, and parameters of the elements and links, as well as on their topology (site implementation). This peculiarity predetermines the need to solve the problem of technological, structural, topological and parametric optimization in the process of reengineering LSMSs.

Since the monitoring practice applies a relatively small set of technologies, types of elements, nodes and links, the most difficult task is optimization of the LSMS structure and topology.

The analysis of contemporary publications on the design of monitoring systems has revealed that the main objective of monitoring systems is collection of the necessary information at minimum cost [6–8].

Minimized additional costs [7] (alongside minimized regular costs), the required or maximized control owing to a multiple coverage of the monitoring zone [8], a maximum coverage of the monitored objects (with regular and irregular coverage radii) [9–11] and a minimized average time of information receipt (optimal operativeness) [12] are used as criteria in the tasks of optimization of monitoring systems. Restrictions on probabilistic supply of information to a specified number of consumers [13] and the location of the monitoring points [14] serve as additional limitations.

Mathematical models and methods for solving the problems of the analysis and synthesis of other large-scale objects in the fields of transportation, communication and logistics can be applied in reengineering LSMSs [7, 15–16].

The analysis has revealed that the most common are monitoring systems with radial nodal structures that contain a single center, one level of nodes and a plurality of elements distributed between the nodes of the system (each node covering its subset of the monitored objects). Design and (or) operation costs as well as operativeness (time of information receipt) costs serve as indicators of the monitoring system efficiency. Therefore, a topical problem lies devising a method that would solve a two-criteria task of reengineering topological structures of LSMSs in terms of the costs and operativeness.

FORMALIZATION OBJECTIVE OF REENGINEERING TOPOLOGICAL STRUCTURES OF LSMSs

Formalization of the generalized LSMS description is based on the suggested in the study [15] scheme for large-scale objects. The LSMS is viewed as a system $S =< E,R,G >$, where: *E* is a set of elements in the system, *R* is a set of relations (links) between the elements, and *G* is a topological implementation of the monitoring system structure <*E, R*>.

Topological implementation of the LSMS is based on the topological complex of elements G_E, relations G_R, and data transmission trajectories G_A. The process of reengineering must distinguish between the subsets of intrinsic and the required properties of the system – P' and P'', respectively. The sets of properties P' and P'' are subsets of the universal set of properties P^U that can be obtained on universal sets of elements E^U, relations R^U, and topologies G^U [15]:

$$P^U = \varphi(E^U, R^U, G^U),$$

where φ is a mapping.

The E^U set consists of various types of elements that can be applied in reengineering LSMSs. The R^U set is determined by the E^U set composition, whereas the latter is determined by composition of the E^U and R^U sets. Meanwhile, the difference between the sets of elements in the new E'' and the existing E' structures determines the set of elements that ought to be included in the new structure:

$$E^+ = E'' \setminus E'.$$

Accordingly, it is possible to identify a subset of elements in the existing LSMS structure that can be excluded from further consideration in the process of reengineering LSMS:

$$E^- = E' \setminus E''.$$

The set of elements E^S, that can be reapplied in reengineering, presented as an intersection of the sets E' and E'':

$$E^S = E' \cap E'', E' = E^S \cup E^-, E'' = E^+ \cup E^S. \qquad (1)$$

Since composition of the sets of relations between the elements R', R'' and the topologies G', G'' is determined by composition of the sets E' and E'', we can identify the corresponding subsets of relations that ought to be included in LSMSs during their reengineering, either reused or not used at all:

$$R^+ = R'' \setminus R', E^- = R' \setminus R'',$$

$$R^S = R' \cap R'', R' = R^S \cup R^-, R'' = R^+ \cup R^S, \qquad (2)$$

$$G^+ = G'' \setminus G', G^- = G' \setminus G'',$$

$$G^S = G' \cap G'', G' = G^S \cup G^-, G'' = G^+ \cup G^S.$$

The scheme of interconnections between such categories as “element”, “relation”, “topology” and “property” in reengineered LSMSs allows introduction of sets of new properties $P^+ = P'' \setminus P'$ and properties that are or can be excluded from consideration $P^- = P' \setminus P''$.

At the first stage, a set of feasible solutions during reengineering LSMS $S^* = \{ s \} \subseteq S''$ is determined by subsets of elements $E^* \subseteq E'' \subseteq E^U$, their relations $R^* \subseteq R'' \subseteq R^U$ and topologies $G^* \subseteq G'' \subseteq G^U$. Further stages of reengineering the topological structure of LSMSs allow selection of subsets of elements $E^o \in E^*$, relations $R^o \in R^*$ and topologies $G^o \subseteq G^*$ from a feasible area $S^* = \{ s \}$. Using the above subsets we obtain a set of the required properties $P'' \subseteq P^U$ that are specified as objective functions, either cost and (or) functional limitations.

The set of tasks (stages) of the structural and topological reengineering LSMS largely coincides with the set of problems of synthesis the initial version LSMS, but will be different by productions, input data and limitations.

According to the suggested in [6] general decomposition scheme for reengineering LSMSs, the meta-level task can be presented as follows:

$$MetaTask = Task_1^0 : \{ Objs, s, Q^*, C^*, S' \} \rightarrow \\ \rightarrow \{ s^o, K(s^o) \}, \qquad (3)$$

where: *Objs* – a set of quantitative and qualitative characteristics of the LSMS objects; *s* – the existing realization LSMS; Q^* – the required set of the system functional qualities; C^* – marginal values of the system cost; S' – the area of reengineering (feasible patterns), s^o – a new LSMS pattern obtained during its reengineering; $K(s^o)$ – criterial assessment of the selected pattern and topology of the LSMS.

The objective of reengineering the topological structure of a three-tier LSMS that is based on the same-type elements, nodes and links and regards reengineering costs as well as operativeness requirements is considered in the following formulation.

Specified:

– a set of the system elements $I = \{ i \}, i = \overline{1,n}$ that cover the entire set of the monitored objects;

– the existing pattern of the topological structure $a \in S$ (where S is a set of feasible topological patterns) determined by the sites of elements $I = \{ i \}, i = \overline{1,n}$, nodes $y' = [y'_i], i = \overline{1,n}$ (where y' is a Boolean variable; if there is an *i*-element based node, $y' = 1;$ otherwise $y' = 0$), the center (the system center is sited on the base of the element $i = 1$), as well as links between the elements, nodes and the center $x' = [x'_{ij}], i, j = \overline{1,n}$ (where x'_{ij} is a Boolean variable; if the elements i and j are linked directly, $x'_{ij} = 1$; otherwise $x'_{ij} = 0$);

– the cost of setting up (operation of) nodes $[c_{ii}]$, $i = \overline{1,n}$ and links $[c_{ij}]$, $i, j = \overline{1,n}$.

It is necessary to identify the optimum in terms of efficiency and cost topological structure $s^o \in S$ (where S is a set of feasible patterns) that is determined by the number of nodes u their sites $y = [y_i], i = \overline{1,n}$ (the central node is sited on the base of the first element, i.e. $y_1 = 1$) and the scheme of links between the elements, nodes and the center $x = [x_{ij}], i, j = \overline{1,n}$ in view of the specified constraints of costs and operativeness.

In order to simplify the model and taking into account the symmetry a square matrix of links (between system elements, nodes and center) and the cost will replace the triangular upper diagonal matrix.

Whereas the initial set of feasible solutions is determined by the following [5]:

$$S = \{s\} = \begin{cases} x = [x_{ij}], x_{ij} \in \{0,1\}, i, j = \overline{1,n}, x_{11} = 1; \\ \sum\limits_{j=i}^{n} x_{ij} \geq 1, \forall j = \overline{1,n}; \\ \sum\limits_{i=1}^{n} \sum\limits_{j=i}^{n} x_{ij} = n + \sum\limits_{i}^{n} x_{ii}; \\ x_{ii} = 1 \rightarrow x_{i1} = 1 \; \forall i = \overline{1,n}; \\ x_{ii} = 1 \wedge x_{ij} = 1 \rightarrow ij = \\ = \arg\min\{\min\limits_{1 < i' \leq j} c_{i'j}, \min\limits_{j < i' \leq n} c_{ji'}\} \; \forall i \leq n, i, j = \overline{1,n}, \end{cases} \tag{4}$$

where S – a set of feasible patterns of topological structures of LSMSs; s – a pattern of the topological structure; $x = [x_{ij}], i, j = \overline{1,n}$ – a matrix of links (where x_{ij} is a Boolean variable; if the elements i and j are linked directly, $x_{ij} = 1$; otherwise $x_{ij} = 0$; if the system node is i-element based, $x_{ii} = 1$; otherwise $x_{ii} = 0$; $i = \overline{1,n}$), n – a number of the system elements, and $[c_{i'j}]$, $i', j = \overline{1,n}$ is the cost of links between the elements i' and j.

The cost of the existing LSMS pattern $C(a), a \in S$ consists of the costs of the center $C_C(a)$, nodes $C_U(a)$, elements $C_E(a)$, and links between the nodes and the center $C_{UC}(a)$ as well as the elements and the nodes $C_{EU}(a)$ [7]:

$$C(a) = C_C(a) + C_U(a) + C_{UC}(a) + C_E(a) + C_{EU}(a). \tag{5}$$

By analogy, estimate the cost $C(b)$ of the optimal pattern LSMS for new conditions of functioning, (excluding the current topological structure $a \in S$) can be represented as:

$$C(b) = C_C(b) + C_U(b) + C_{UC}(b) + C_E(b) + C_{EU}(b). \tag{6}$$

A desirable goal consists in minimizing the additional costs $\Delta C(a,b)$. Meanwhile, the difference in the costs (5) and (6)

$$\Delta C(a,b) = C(a) - C(b), \tag{7}$$

fails to account for the possible use of parts of the existing topological structure $a \in S$.

In view of the above equation (7), a particular criterion of the minimum additional costs:

$$k_1(a,s) \rightarrow \min_{s \in S},$$

(with the possible use of a part of the existing topological structure $a \in S$) can be presented as follows:

$$k_1(a,s) = \Delta C(a,s) = \sum_{i=1}^{n} [(c_i + e_i)(1 - x'_{ii})x_{ii} + (d_i - g_i)x'_{ii}x_{ii}] +$$

$$+ \sum_{i=1}^{n} \sum_{j=1}^{n} [(c_{ij} + e_{ij})(1 - x'_{ij})x_{ij} + (d_{ij} - g_{ij})x'_{ij}x_{ij}] \rightarrow \min_{s \in S}, \tag{8}$$

where c_i – the cost of the elements, nodes and the center in the new structure, $i = \overline{1,n}$; x'_{ij} and x_{ij} – respectively, elements of the matrices of adjacency (links) between the elements, nodes and the center in the existing structure $x' = [x'_{ij}]$ and in the reengineered structure $x = [x_{ij}]$ (if the elements i and j are linked directly, $x'_{ij} = 1$ or $x_{ij} = 1$; otherwise $x'_{ij} = 0$ or $x_{ij} = 0$); d_i – the cost of modernizing an element, a node, or the center in the new structure $i = \overline{1,n}$; e_i – the cost of dismantling the nodes in the existing structure $i = \overline{1,n}$; g_i – the cost of resources that can be reused after dismantling the nodal equipment $i = \overline{1,n}$; $[c_{ij}], i, j = \overline{1,n}$ – the cost of links between the elements i and j; and S – a set of feasible patterns of the topological structures of LSMSs.

The second desirable objective is minimizing the maximum time for receipt of the information on the monitored objects. The task under consideration allows use of the deterministic operativeness model that takes into account the dependence of information time on the system's topological structure. The model would facilitate assessment of the strictly specified operation technology that determines the intensity of the same-type flows of information from and to the center:

$$\alpha_i = [\alpha_i], \alpha_i = const, \beta_i = [\beta_i], \beta_i = const, i = \overline{1,n}$$

in the channels and nodes of the system.

The entire time of information receipt from each element of the system $I = \{i\}, i = \overline{1,n}$ can be presented as consisting of the following time intervals: (1) receipt of a request from the center τ_i^C, (2) transmission of the request via the center-node channel τ_i^{CU}, (3) processing of the request in the node τ_i^{U1}, (4) transmission of the request via the node-element channel τ_i^{UE}, (5) receipt of the information by the system element τ_i^{E}, (6) transmission of the response via the element-node channel τ_i^{EU}, (7) processing of the response in the node τ_i^{U2}, and (8) transmission of the response via the node-center channel τ_i^{UC}:

$$\begin{aligned} k_2(s) = \tau_i(s) = \tau_i^{C} + \tau_i^{CU}(s) + \tau_i^{U1}(s) + \tau_i^{UE} + \\ + \tau_i^{E} + \tau_i^{EU} + \tau_i^{U2}(s) + \tau_i^{UC}(s), i = \overline{1,n}. \end{aligned} \tag{9}$$

The time intervals for transmission of requests and responses via the channels center-node $\tau_i^{CU}(s)$, element-node $\tau_i^{EU}(s)$ as well as processing of requests and responses in the nodes $\tau_i^{U1}(s)$, $\tau_i^{U2}(s), i = \overline{1,n}$ depend on the amount of elements connected to each of the nodes (of the LSMS topological structure). Meanwhile, time intervals for receipt of a request from the center τ_i^{C}, receipt of the information by the system element τ_i^{E} and transmission of the response via the element-node channel τ_i^{EU} are independent from the system's topological structure.

Since a desirable goal is minimizing the maximum time for receipt of the information on the monitored objects, the efficiency criterion (based on the above equation (9) can be presented as follows:

$$k_2(s) = \max_{1 \le i \le n} \left[\begin{aligned} & \tau_i^{C} + \frac{\alpha_i}{q_{ij}} + \tau_i^{E} + \frac{\beta_i}{q_{ij}} + \\ & + \left(\frac{\alpha_i}{q_i} + \frac{\alpha_i}{h_i^1} + \frac{\beta_i}{h_i^2} + \frac{\beta_i}{q_i} \right) \sum_{i=1}^{n} \sum_{j=i}^{n} x_{ij} x_{ii} \end{aligned} \right] \to \min_{s \in S}, \tag{10}$$

where: q_i and q_{ij} – bandwidths of the center-node and node-element channels; h_1 and h_2 – velocities of processing the request and the response in the system nodes.

When the monitoring system uses a not strictly deterministic data collection technology that causes heterogeneous flows in the network, the correlations (9) – (10) are used for preliminary assessment of the operativeness. Imitation models would secure a reliable assessment of the time for information receipt in LSMSs [17–18].

A METHOD FOR REENGINEERING THE TOPOLOGICAL STRUCTURES

A mathematical model of a two-criteria task of reengineering the LSMS topological structures includes formalized criteria of costs (8) and operativeness (10):

$$\begin{cases} k_1(a,s) \to \min\limits_{s \in S}, k_1(a,s) \le k_1^*; \\ k_2(s) \to \{ \max\limits_{1 \le i \le n} \tau_i \} \to \min\limits_{s \in S}, k_2(s) \le k_2^* \end{cases}, \tag{11}$$

where: k_1^* and k_2^* – marginal values of costs on reengineering $k_1(a,s)$ and operativeness $k_2(s)$, respectively.

A set of feasible solutions (4) generally consists of two subsets $S = S^S \bigcup S^K$, where S^S is a subset of agreement, in which particular criteria of costs $k_1(a,s)$ and efficiency $k_2(s)$ can change concertedly, while S^K is a subset of compromise (effective options), in which particular criteria of costs $k_1(a,s)$ and efficiency $k_2(s)$ are strictly contradictory.

An optimal solution of any multi-criteria objective belongs to the area of compromise [21]. In a solvable discrete two-criteria objective (11), an optimal solution $s^o \in S$ belongs to a subset of compromise $s^o \in S^K \subseteq S$. None of solutions of the S^K subset can be improved by all particular criteria simultaneously. In view of the latter, selection of the best option of topological structures $s^o \in S$ for LSMSs consisting of relatively few elements ought to be accompanied by formation of a set of alternatives S and a subset of compromise S^K. The approach is as follows [22].

The first of generated options s is integrated in the set S^K. Each of further alternatives $s' \in S$ is compared to each option belonging to the set of compromise $s \in S^K$. If a generated option $s' \in S$ is the best of all subset S^K options in terms of costs and efficiency, it is integrated in the subset of effective options S^K. If an option $s' \in S^K$ is worse than the new one $s' \in S$, it is excluded from the subset S^K.

When the generation of alternative options $s \in S$ (4) is completed, the subset of effective options S^K is formed. In general, $Card\ S^K << Card\ S$ which allows a considerable reduction of the memory capacity to store alternative options and save time for their further analysis.

The method of hierarchy analysis [23] is suggested for selecting the only solution from the subset of effective options $s^o \in S$.

Given the volumes of the existing LSMS and the initial set of feasible solutions (4), the set of effective solutions (11) can be quite potent. Therefore, the best compromise solution $s^o \in S$. ought to be found with the cardinalist approach aided by the additive function of general utility:

$$P(s) = \eta_1 \xi_1(s) + \eta_2 \xi_2(s) \to \max_{s \in S}, \tag{12}$$

where: η_i – coefficients of significance of particular criteria

$$\begin{aligned} k_i(s), 0 \le \eta_i \le 1, i = \overline{1,2}, \eta_1 + \eta_2 = 1; \\ \xi_i(s) = [(k_i(s) - k_i^-)/(k_i^+(s) - k_i^-)]^{\mu i}, \end{aligned} \tag{13}$$

where: $k_i(s)$, k_i^-, $k_i^+(s)$, $i = \overline{1,2}$ – the current (for an option $s \in S$), the worst and the best values of a particular criterion i; $\eta_i, i=\overline{1,2}$ – a weight coefficient of a particular criterion i, and $\mu_i, i=\overline{1,2}$ is a parameter that determines the type of the utility function of a particular criterion i.

The analysis of the objective functions (8) and (10) revealed that the envelopes of their local extrema are single-extreme dependences on the number of nodes in the system. Therefore, the maximum point of the general utility function (12) is between the minima of the cost function (8) and the efficiency function (10) by the number of nodes in the system u.

Therefore we suggest that the task of reengineering of the LSMS topological structures should be solved with the method of a directed enumeration of local extrema of the objective function (12).

The method can be applied via preliminary assessment of weight coefficients $\eta_i, i=\overline{1,n}$ as well as parameters $\mu_i, i=\overline{1,n}$ of the utility functions of particular criteria (12) – (13). They can be found by means of the methods of expert assessment or comparatory identification [19–20].

The method of comparatory identification of the pattern of multi-factor assessment (12) consists in the following. A decision-maker or an expert determines the qualitative utility on the set of options $s \in S^K$ going by the values of particular criteria of cost (8) and operativeness (10). The qualitative utility can be expressed by a set of binary relations of equivalence, of lax and strict preferences:

$$R_E(S^K)=\{(y,z): y,z \in S^K, y \succ z\},$$
$$R_{NS}(S^K)=\{(y,z): y,z \in S^K, y \succ z\},$$
$$R_S(S^K)=\{(y,z): y,z \in S^K, y \succ z\}$$

and generally represented by the order of one of the following functions:

$$\begin{aligned} &R_E^O(S^K): s^o \approx s_i \approx s_j \approx \ldots \approx s_m, \\ &R_{NS}^O(S^K): s^o \geq s_i \geq s_j \geq \ldots \geq s_m, \qquad (14) \\ &R_S^O(S^K): x^o \succ x_i \succ x_j \succ \ldots \succ s_m, \end{aligned}$$

where: m – capacity of the subset of options used in selection of the pattern parameters (12) – (13).

Systems of equations and (or) inequalities are based on the set order of alternatives (14) and complemented by the following ratios:

$$0 \leq \eta_i \leq 1, \mu_i > 0, i=\overline{1,2} \text{ и } \eta_1+\eta_2=1.$$

The best values of parameters can be selected by the criterion of the minimum error in the recovery of the decision-maker's (expert's) preferences.

However such formulation of the task is not correct (by Hadamard). In general, such task may have no solution at all (if the decision-maker mistakenly has specified preferences $R^O(s)$), or have more than one solution. The only solution can be found by means of a regularized original task, i.e. an additional criterion. Preferences based on the relationship of strict preference $R_S(S^K)$ are found due to such criteria as the maximized minimum difference of the general utility function (12) of adjacent options $s_j, s_{j+1} \in R_S^O(S^K)$ or the maximum sum of their differences.

Preferences that can be expressed as a ratio of equivalence $R_E(S^K)$ are provided with such criterion as the minimum sum of the modules of values difference in the general utility function (12). A lax preference $R_{NS}(S^K)$, requires pre-selection of binary relations of the strict preference $R_S(S^K)$ and the equivalence $R_T(S^K)$.

The method of a directed enumaration of local extrema of the objective function (12) is as follows. Presumably the system lacks nodes, i.e. $u=0$. The general utility function's (12) value is calculated for the known values of the weight coefficients $\eta_i, i=\overline{1,n}$ and parameters $\mu_i, i=\overline{1,n}$ of the utility functions of particular criteria. If the selected topological structure satisfies the constraints of the objective (11), the obtained value of the generalized criterion is viewed as record $P^*(s^o)=P(s,u=0)$, and the obtained option – as locally optimal s^o.

Let us increase the number of nodes: $u=1$. Analyzing the options for the topological structure with a single node we find the best option among those which meet the objective constraints: $P^*(s,u=1)$.

If $P^*(s,u=1) < P^*(s^o)$, the best option is s^o, where the number of nodes is $u=0$. Otherwise, we increase the number of nodes in the system ($u := u+1$) and distinguish best option of the topological structure among those which satisfy the objective constraints until the value of $P*(s,u)$ decreases $P*(s^o)$.

CONCLUSION

1. The study formulates the task and presents a new mathematical model for reengineering the topological structures of centralized three-tier large-scale monitoring systems (LSMSs) in view of the indices of efficiency and cost, which is aimed at optimization of large-scale objects.

2. The analysis of objective functions of the task has revealed that such functions are one-extreme (relative to the number of nodes in the system). On this basis, we have suggested the method of a directed inspection of local extrema of the objective function to solve the problem of reengineering the topological structures in terms of their efficiency and cost. In contrast to the methods of exhaustive search, the suggested approach considerably narrows the search area and facilitates the search of effective solutions.

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