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FORMALIZATION OF THE PROBLEM OF TRANSPORT LOGISTICS OPTIMIZATION NETWORKS AT THE STAGE OF REENGINEERING

The **subject** of research in the article is the process of supporting decision-making in the tasks of optimizing closed logistics networks at the stage of reengineering. The **goal** of the work is to improve the efficiency of technologies for the automated design of closed logistics networks due to the improvement of mathematical models of multi-criteria problems of reengineering their topological structures. The following **tasks** are solved in the article: review and analysis of the current state of the problem of supporting decision-making in the tasks of optimizing logistics networks at the stage of their reengineering; decomposition of the problem of optimization of logistics networks at the main stages of their life cycles; selection of a logical scheme of the reengineering process of the logistics network as a territorially distributed object; development of a mathematical model of the general problem of multi-criteria optimization of logistics networks according to indicators of economy, efficiency, reliability and survivability; selection of models for scalar multi-criteria evaluation of reengineering options, taking into account factors that are difficult to formalize, knowledge and experience of the decision-maker. The following **methods** are used: system approach, theories of systems, theories of usefulness, theories of decision-making, system design, optimization and operations research. **Results.** Decomposition of the reengineering problem was carried out on the following tasks: determination of the purpose of reengineering and the principles of network reconstruction; network structure optimization; optimization of the topology of network elements; selection of functioning technology; determination of parameters of elements and vehicles; assessment and selection of the best network construction option. The general mathematical model of the multi-criteria task of reengineering the topological structures of centralized three-level logistics networks based on the indicators of costs, cargo delivery time, reliability and survivability has been improved. Universal functions of general utility and utility of local criteria are proposed to obtain scalar estimates for multiple indicators. Exclusion of part of local criteria and restrictions from the general model allows obtaining models of practically all interesting problems of optimization of logistics networks. **Conclusions.** The developed complex of mathematical models expands the methodological principles of automating the processes of designing logistics networks, allows for the correct reduction of a set of effective options for their construction for the final choice, taking into account factors that are difficult to formalize, the knowledge and experience of designers. The practical use of the proposed complex of mathematical models will reduce the time and capacity complexity of project decision-making support technologies, and due to the use of the proposed options selection procedures, increase their quality based on a number of functional and cost indicators.

Keywords: logistics network; design technology; optimization; reengineering; multi-criteria evaluation; decision support.

Introduction

The efficiency of production and sales processes of modern companies is largely determined by the quality of their logistics, which traditionally covered the processes from the development of sources of raw materials to the supply of finished products to the final consumer [1 - 3]. The next stage in the development of logistics was the management of material, financial and information flows in supply chains. At the same time, one of the more fundamental planning frozen in supply chain management (SCM) is the supply chain network design (SCND) [4]. Under increasing environmental constraints, logistics activities have encompassed the entire cycle from optimal use of raw materials to the disposal of waste activities. The methodology of environmental ("green") logistics is aimed at reducing the risks of environmental degradation and improving the environmental and economic efficiency of companies [5 - 6]. The reversible and closed-loop logistics, which cover the tasks of optimization of reverse inventory, information, money flows, are rapidly developing within the environmental framework [4 - 7].

Changes in the nomenclature and demand for products, location of production facilities and recycling or disposal centers (containers, waste, substandard products, etc.), used vehicles, expansion of the consumer network at a certain stage leads to the need to reengineer existing logistics networks [8]. In general, logistics reengineering involves solving a set of tasks: determining the objectives of the reorganization of the logistics network; identification of operations subject to reengineering; system analysis and development of the reengineering option; evaluation and comparative analysis of the proposed reengineering option; implementation of the reengineering project. At the same time, design and management decisions on reengineering of supply chains (SC) in dynamic business environments should be sufficiently flexible and viable. This, as well as the need to take into account the reverse flows in the processes of closed logistics, generates many new tasks that require system formalization and development of effective methods for their solution [9-10].

Analysis of the current state of the problem and methods of its solution

Reverse and closed-loop logistics are considered one of the effective means of reducing environmental pollution and resource consumption through the recycling and recovery of used products [11 - 13]. At the same time, the theory of optimization of logistics networks with both single and multiple options for recycling or recovery of goods is being developed [14 - 15]. Regardless of the type of structures, networks of both traditional and closed logistics systems usually cover significant areas. Their structural, functional and cost characteristics are largely determined by their topology (location of production, processing, recycling, hubs, and consumers). This feature allows us to classify closed logistics systems into the class of territorially distributed objects [16]. The problem of

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optimizing such objects belongs to the poorly structured. It contains a set of tasks not fully defined in terms of goals and data, for which no technologies for effective solutions have been designed. The methodology of structural synthesis of such objects is based on the ideas of aggregate-decomposition and block-hierarchical approaches. This involves dividing the description of closed-loop logistics systems into hierarchical levels and aspects, and the optimization process – into groups of procedures related to obtaining and transforming descriptions (solutions) on the selected levels and aspects. Subsequently, the descriptions obtained are combined to receive generalized solutions at the appropriate level.

Traditionally, the optimization problem for such objects is considered as a meta-problem $MetaTask$, the decomposition of which establishes a set of interrelated local problems:

$$MetaTask = \{ Task^l \},\ Task^l = \{ Task_i^l \},\ i = \overline{1,i_l}\ ,\ l = \overline{1,n_l}\ , \quad (1)$$

where $Task^l$ – set of tasks of the l-th decomposition level; $Task_i^l$ – i-th local task of the l-th level; i_l – number of local tasks at the l-th level; n_l – number of levels of problem decomposition.

At the three-level decomposition scheme (fig. 1), the tasks of system optimization of the logistics network as a territorially distributed design object are distinguished at the macro level [8, 10, 16]. They reflect the features of the main stages of its life cycle and differ only in terms of constraints: $Task_1^1$ – formation of network creation goals and development of the terms of reference for its design; $Task_2^1$ – system design; $Task_3^1$ – network development planning; $Task_4^1$ – network modernization; $Task_5^1$ – network reengineering.

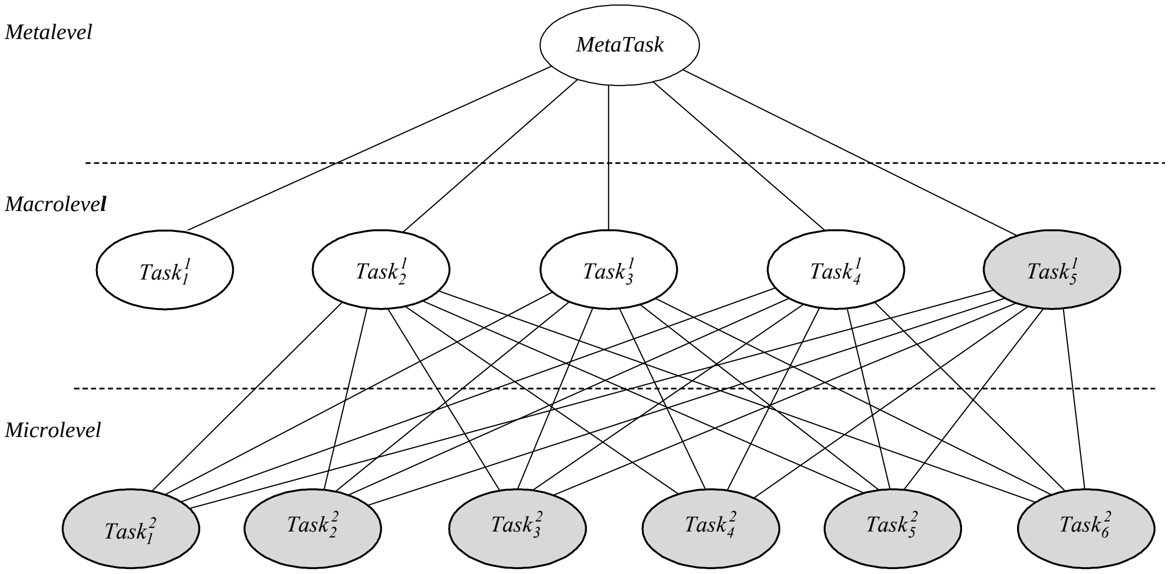

Fig. 1. Decomposition scheme of the logistics network optimization problem as a regionally distributed object [16]

Optimization of transport logistics networks in the process of reengineering at the lower level involves solving a set of interrelated tasks (fig. 1): $Task_1^2$ – determination of reengineering objectives and principles of network reengineering; $Task_2^2$ – optimization of network structure; $Task_3^2$ – optimization of network elements topology (production, processing or recycling points, hubs); $Task_4^2$ – choice of functioning technology; $Task_5^2$ – determination of elements and transport means parameters; $Task_6^2$ – evaluation and choice of the best option of network construction.

In this case, each of the allocated local problem tasks $Task_i^l\ ,\ i = \overline{1,i_l}$ is considered as a transformer of its input data In_i^l into its output data Out_i^l :

$$Task_i^l : In_i^l \to Out_i^l\ ,\ l = \overline{1,n_l}\ ,\ i = \overline{1,i_l}\ . \quad (2)$$

For an estimation of design decisions the methodology of the functional-cost analysis which assumes a maximization of efficiency of variants of network construction $P(s) \to \max\limits_{s \in S^*}$ (where S^* is a set of admissible variants of network reengineering) is used. For an estimation of efficiency in practice, the ratio of the received effect from use of a network $Q(s)$ and expenses for its achievement $C(s)$ is used [10]:

$$Q(s) = F_1(E,\ R,\ G)\ ,\quad C(s) = F_2(E,\ R, G)\ , \quad (3)$$

where $E,\ R,\ G$ – respectively the set of network elements, links between elements and their topologies, determining the locations of the elements; F_1, F_2 – some mappings establishing the dependencies of effect and costs on the characteristics of the network $s = < E,\ R, G >$.

Under the given constraints on the scalar effect $Q(s) \geq Q^*$ and (or) cost $C(s) \leq C^*$ indicators, the problem of reengineering the logistics network is formally presented in the following form:

$$s^o = \arg\max_{S \in S^*}\{[P(s) = Q(s)/C(s)] : Q(s) \geq Q^*,\ C(s) \leq C\}. \qquad (4)$$

Under the condition of a single constraint on the effect $Q(s) \geq Q^*$ or cost $C(s) \leq C^*$ indicators, problem (4) is transformed into the problem of maximizing the effect of using the network under given constraints on resources:

$$s^o = \arg\max_{s \in S^*}(Q(s) : C(s) \leq C^*), \qquad (5)$$

or cost minimization under given constraints on the effect of using the network:

$$s^o = \arg\min_{s \in S^*}(C(s) : Q(s) \geq Q^*). \qquad (6)$$

Based on the decomposition of the problem (1) and reengineering goal setting and network reengineering principles $Task_1^2$ (4), a network model of the basic problem is created [17]. Based on this model, a logical scheme for obtaining a design solution is created, which will determine the order of solving local tasks of network reengineering $Task_i^2$, $i = \overline{1,6}$. For its construction, a tuple of sets is defined:

$$CirDes = < Tasks, In, Res, DesDec, ProcDec >, \qquad (7)$$

where $Tasks = \{Task_i^2\}$, $i = \overline{1,6}$ – ordered set of network reengineering tasks; In – set of task tuple input data $Tasks$; Res – set of task constraints; $DesDec$ – set of options for reengineering the network; $ProcDec$ – a problem-solving procedure that establishes a correspondence between tuples $< In, Res >$ and sets of corresponding design solutions $DesDec$.

At that, the models of each of the logistics network reengineering tasks $Task_i^2$, $i = \overline{1,6}$ are presented in the following form:

$$ModTask_i^2 : \{In_{iE}^2, In_{iI}^2, Res_i^2\} \rightarrow DesDec_i^2,\ i = \overline{1,6}, \qquad (8)$$

where In_{iE}^2, In_{iI}^2 – respectively the sets of external and internal with respect to the set of tasks of reengineering of the input data-network $Task_5^1$ of the i-th local task.

For the correct solution of the problems $Task_2^2$, $Task_3^2$, $Task_4^2$, $Task_5^2$ і $Task_6^2$ and information on the solutions of previous problems is used. To obtain it, it is proposed to use an iterative logical scheme that provides for cyclic implementation of procedures for generation, analysis of reengineering options and selection of the best among them (fig. 2).

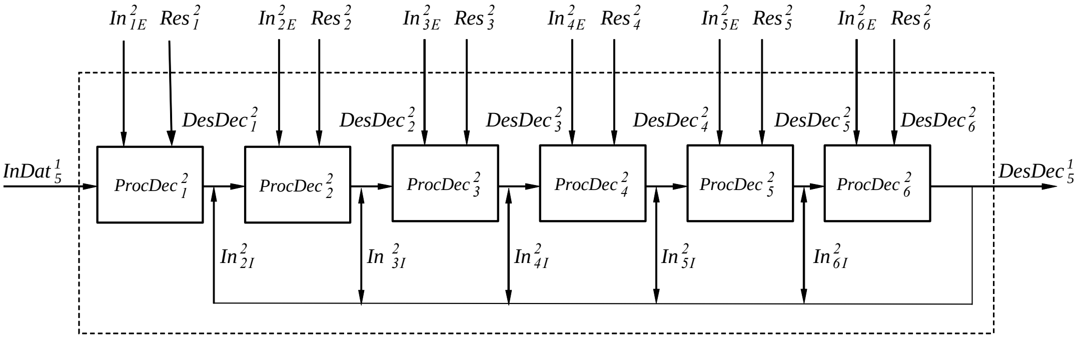

Fig. 2. Iterative logical scheme of reengineering a logistics network as a regionally distributed object [17]

Assessment of the properties of options for reengineering the logistics network is carried out using a set of local cost and functional criteria (cost of goods delivery, time of goods delivery, reliability, survivability of the system, etc.) $K(s) = [k_1(s), k_2(s), ..., k_m(s)]$ [8, 10]:

- costs involved $k_1(s) \rightarrow \min_{s \in S^*}$;
- cargo delivery time: $k_2(s) \rightarrow \min_{s \in S^*}$;
- network reliability (availability factor): $k_3(s) \rightarrow \max_{s \in S^*}$;
- network survivability (share of consumers who receive cargo when its components are damaged): $k_4(s) \rightarrow \max_{s \in S^*}$.

Taking into account the constraints on cost and functional indicators of options mathematical model of multi-criteria problem of optimization of the logistics network is represented in the following form:

$$k_1(s) \longrightarrow \min_{s \in S^*} : k_1(s) \leq k_1^*;\ \ k_2(s) \rightarrow \min_{s \in S^*} : k_2(s) \leq k_2^*;\ \ k_3(s) \rightarrow \max_{s \in S^*} : k_3(s) \geq k_3^*;\ \ k_4(s) \rightarrow \max_{s \in S^*} : k_4(s) \geq k_4^*, \qquad (9)$$

where k_1^*, k_2^*, k_3^*, k_4^* – limit acceptable values of cost indicators, responsiveness, reliability and survivability of the logistics network.

To choose the best option of network reengineering from the set of admissible $s^o \in S^*$ in the process of problem solution utility theory models are applied with the use of methods of quantitative or qualitative estimation [18 - 20]. At the same time, it is recommended to remove a subset of dominant (inefficient) variants of network $\overline{S}$ construction from the set of admissible ones [21]. After that, the choice will be made only from the set of effective (Pareto-optimal) options:

$$S^E = S^* \setminus \overline{S}\,, \quad S^E \cap \overline{S} = \varnothing\,, \quad S^E \cup \overline{S} = S^*\,. \qquad (10)$$

The procedure of compilation and selection on small sets of effective network S^E reengineering options is carried out by decision makers (designers) using methods of multicriteria analysis, the most common among which include AHP, MAUT, TOPSIS, PROMETHEE, ELECTRE [22 - 23]. Each of the methods uses a different technology to evaluate decisions, so different variants of reverse engineering can be established as the best. Recently, the comparator identification method, which allows to synthesize a function for quantitative scalar evaluation of the whole set of reengineering variants on the basis of some revealed order on the set of effective variants $P(s)$, $s \in S^E$ has become popular [21, 24].

The most widespread for scalar multicriteria evaluation of options is additive convolution of local criteria using relatively simple functions of their utility [21, 24]:

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

$$\xi_j(s) = \{[k_j(s) - k_j^-] / [k_j^+ - k_j^-]\}^{\mu_j}\,, \qquad (11)$$

where λ_j – coefficients of local criteria importance $k_j(s)$, $j = \overline{1,m}$, $\lambda_j \ge 0$, $\sum_{j=1}^{m} \lambda_j = 1$; $\xi_j(s)$ – value of the utility function of the j-th local criterion for the network reengineering option s; k_j^-, k_j^+, $j = \overline{1,m}$ – the worst and the best value of the j-th criterion on the admissible set of variants S^*; μ_j – the parameter defining a particular kind of function $\xi_j(s)$: concave, convex or linear.

According to the results of the review of the current state of the problem of optimization of transport logistics networks at the stage of reengineering, it was found that:

- the existing models of the problems of reengineering of logistics networks (1) - (8) determine only the relationship of the tasks by variables and parameters and do not allow to obtain quantitative estimates of the options by a variety of functional and cost indicators;
- problems of structural and topological optimization of logistic networks refer to the class of multi-criteria, have combinatorial nature, and the vast majority of options for building networks, analyzed in the process of their solution, are ineffective;
- there is a need to improve mathematical models of structural and topological optimization problems of logistic networks for quantitative assessment of network reengineering options on the set of functional and cost indicators.

In this regard, the aim of the article is to improve the efficiency of automated design technologies of closed logistics networks by improving the mathematical models of multi-criteria problems of reengineering their topological structures.

Research results

Let us consider the problem of optimizing a closed logistics network with integrated centers (production and processing points) according to the four local criteria of economy, efficiency, reliability, and survivability. The indicators of economy and efficiency are traditional in solving the problems of optimization of logistics networks, and the indicators of reliability and survivability are important for military logistics and logistics of critical systems [25].

The problem of reengineering the topological structure of a centralized three-level logistics network is considered in the formulation [8, 10]. Given: the set of elements of the existing network $I = \{i:\ i = \overline{1,n}\}$; the existing variant of the topological structure of the network $s' \in S^*$, specified by the locations of consumers, nodes, center (coincides with the location of the element $i = 1$), as well as the links between consumers, nodes and center $[s'_{ij}]$ $i,j = \overline{1,n}$ ($s'_{ij} = 1$ if there is a direct connection between the elements i and j and $s'_{ij} = 0$ – if not); the costs of creation (upgrading), operation of nodes c_i, $i = \overline{1,n}$ implementation of transportation c_{ij}, $i,j = \overline{1,n}$, the cost of resources that can be re-used (or sold) after the dismantling of equipment nodes and transport means.

It is necessary to determine the best option in terms of cost, efficiency, reliability and survivability of the topological structure of the logistics network $s^o \in S^*$ (7).

The set of admissible variants of topological structures of the centralized three-level network can be represented in the following way:

$$S = \{s\} = \begin{cases} [s_{ij}], \quad s_{ij} \in \{0,1\}, \quad i,j = \overline{1,n}, \ s_{11} = 1; \\ \sum\limits_{i=j}^{n} s_{ij} \ge 1, \ \forall j = \overline{1,n}; \\ \sum\limits_{j=1}^{n} \sum\limits_{i=j}^{n} s_{ij} = n + \sum\limits_{i=1}^{n} s_{ii}; \\ s_{ii} = 1 \rightarrow s_{i1} = 1 \ \ \forall i = \overline{1,n}; \\ s_{ii} = 1 \wedge s_{ij} = 1 \rightarrow ij = arg \min\limits_{i \le j \le n} c_{ji} \ \ \forall i,j = 1,n. \end{cases} \qquad (12)$$

The main constraints for a three-level centralized network, presented in conditions (12): each consumer in the network must be connected to one of the nodes or directly to the center; more than one consumer must be directly connected to each node; each consumer i is connected to terminal j by an indicator of minimum reduced costs; each of the nodes in network j has a direct connection to the center; the number of nodes in the network is in the range $1 \le \sum_{i=j}^{n} s_{ii} \le n/2$; total number of direct connections in the network structure is $\sum_{j=1}^{n}\sum_{i=j}^{n} s_{ij} = n + \sum_{i=1}^{n} s_{ii}$.

The local criterion for the cost of reengineering the logistics network in the above designations can be represented in the following form:

$$\begin{aligned} k_1(s', s) = \sum_{i=1}^{n} [c_i(1 - s'_{ii})\, s_{ii} + d_i s'_{ii} s_{ii} + e_i(1 - s_{ii})\, s'_{ii} - g_i(1 - s_{ii})\, s'_{ii}] + \\ + \sum_{j=1}^{n}\sum_{i=j}^{n} [c_{ij}(1 - s'_{ij})\, s_{ij} + d_{ij} s'_{ij}\, s_{ij} + e_{ij}(1 - s_{ij})\, s'_{ij} - g_{ij}(1 - s_{ij})\, s'_{ij}] \to \min_{s \in S^*}, \end{aligned} \tag{13}$$

where c_i – the cost of creating a i-th consumer-based node; $i = \overline{1,n}$; s'_{ij}, s_{ij} – elements of the matrices of connections between elements in the existing network $s' = [s'_{ij}]$ and in the network structure after reengineering $s = [s_{ij}]$; d_i – given the cost of upgrading a i-th consumer-based node; e_i – the cost of removing a i-th consumer-based node in the existing network; g_i – the cost of resources that can be reused after the removal of i-th consumer-based node equipment; c_{ij} – the given cost of transporting goods between elements i and j, $i, j = \overline{1,n}$.

The local efficiency criterion for a three-tiered centralized network defines the maximum delivery time to the entire set of consumers:

$$k_2(s) = [\max_{i} \sum_{i=1}^{n} \tau_{1i} s_{1i} + \max_{i} \sum_{i=1}^{n} \tau_i s_{ii} + \max_{i,j} \sum_{i=1}^{n}\sum_{i=1}^{n} \tau_{ij} s_{ij}] \to \min_{s \in S^*}, \tag{14}$$

where τ_{1i} – time of cargo transportation from the production center to the node at the base of the i-th consumer; τ_i – time of cargo handling at the node at the base of the i-th consumer; τ_{ij} – time for cargo delivery from the node at the base of the i-th consumer to the j-th consumer.

When assessing the reliability of logistics network options, we take into account the reliability of production equipment, node equipment, and vehicles in use. We will assume that the equipment of the nodes of the logistics network and the vehicles used have the same reliability. In the local reliability criterion, we propose to use the coefficient of network availability for the full performance of the function of cargo delivery:

$$k_3(s) = h_1 \times (h_2)^{u(s)} \times (h_3)^{u(s)} \times (h_4)^n \to \max_{s \in S}, \tag{15}$$

where h_1, h_2, h_3, h_4 – availability coefficients of the equipment of the center, node, transport means used between the center and nodes, as well as between the nodes and consumers; $u(s) = \sum_{i=1}^{n} s_{ii}$ – number of nodes in the network.

When estimating the survivability, we will assume that the consumers of the logistics network receive approximately the same amount of cargo (have approximately the same weight for the sender). While estimating the survivability of the network, we can use the value of the share of consumers receiving cargoes in case of single damage of its components. In this case irrespective of the topological structure of the network, when the center equipment is damaged $k_4(s) \equiv 0$, and when a single vehicle is damaged between the nodes and the end users $k_4(s) \equiv (n-1)/n$. From the point of view of survivability, the damage of a node causes the same network losses as the damage of the vehicle between the center and the node. Considering this, the survivability maximization criterion, taking into account the damage of the vehicle between the center and the nodes, as well as the node equipment, can be represented in the following form:

$$k_4(s) = \left\{ \min_{1 \le j \le n} \left\{ (n - \sum_{j=2}^{n}\sum_{i=j}^{n} s_{ji} s_{ii})/n \right\} \right\} \to \max_{s \in S}. \tag{16}$$

To estimate the values of local criteria, we use the most effective in terms of the complex indicator "accuracy-complexity" function that allows to reproduce not only linear, but also non-linear, including *S*- and *Z*-shaped approximations. [21]:

$$\xi(s) = \begin{cases} \bar{a}(b_1 + 1)\left(1 - \left(b_1 / \left(b_1 + \dfrac{\bar{k}(s)}{\bar{k}_a}\right)\right)\right), 0 \le \bar{k}(s) \le \bar{k}_a; \\ \bar{a} + (1 - \bar{a})(b_2 + 1)\left(1 - \left(b_2 / \left(b_2 + \dfrac{\bar{k}(s) - \bar{k}_a}{1 - \bar{k}_a}\right)\right)\right), \bar{k}_a < \bar{k}(s) \le 1, \end{cases} \tag{17}$$

where $\xi(s)=\overline{k}(s)$; $\overline{k}_a, \overline{a}$ – coordinates of the glue point of the function, $0 \le \overline{k}_a \le 1$, $0 \le \overline{a} \le 1$; b_1, b_2 – parameters determining the type of dependence on the two segments of the function

To quantify the overall usefulness of options for reengineering logistics networks on the four indicators, we will use a universal function constructed using the Kolmogov-Gabor polynomial [21, 24]:

$$P(s)=\sum_{i=1}^{4}\lambda_i\xi_i(s)+\sum_{i=1}^{4}\sum_{j=i}^{4}\lambda_{ij}\xi_i(s)\xi_j(s)+\sum_{i=1}^{4}\sum_{j=i}^{4}\sum_{l=j}^{4}\lambda_{ijl}\xi_i(s)\xi_j(s)\xi_l(s)+\sum_{i=1}^{4}\sum_{j=i}^{4}\sum_{l=j}^{4}\sum_{k=l}^{4}\lambda_{ijlk}\xi_i(s)\xi_j(s)\xi_l(s)\xi_k(s), \quad (17)$$

where λ_i, λ_{ij}, λ_{ijl}, λ_{ijlk} – weighting coefficients assessing the mutual importance of the criteria $k_i(s)$, $k_j(s)$, $k_l(s)$, $k_k(s)$ and their products; $0<\xi_i(s)<1$, $i=\overline{1,m}$ – value of the utility function of the local criterion $k_i(s)$, $i=\overline{1,m}$ (17) for the option $s \in S^E$.

It is proposed to solve the problem of optimizing the logistics network using the combined method [21].

In the framework of this method, it is proposed not to form a set of admissible options for reengineering S^*, but in the process of generation using modifications of the directed search method to form a subset of effective options S^E at once. The total number of possible variants of topological structures in the reengineering of a three-level centralized network for the number of terminals $1<u\le n/2$ is [8]:

$$N(n)=\frac{1}{2}\sum_{u=1}^{n}C_n^u=\frac{1}{2}\sum_{u=1}^{n}\frac{n!}{u!(n-l)!}=2^n/2, \quad (16)$$

where n – the number of places of possible placement of nodes (network consumers).

Thus, the quantity of effective variants is essentially less and their share decreases with the growth of dimensionality of the problem (tab. 1, fig. 3 - 4). Due to the significant reduction of variants, subject to the analysis, it allows to significantly reduce the time of solving the problem. Next, on the set of effective variants S^E, let us define a subset of variants $S' \subseteq S^E$ for preliminary estimation by designers [21]. On it with the use of comparator identification technology we will carry out a structural-parametric synthesis of the function of the total utility of the variants $P(s)$. This will allow based on the values $P(s)$ to carry out the ranking of options from the set of effective S^E and provide the necessary number of them for the final choice of the decision maker.

Table 1. *Capacities of a subset of effective logistics network reengineering options for* $m=4$

$\lvert S^*\rvert$	10000	20000	30000	40000	50000	60000	70000	80000	90000	100000
$\lvert S^E\rvert$	151	195	216	253	268	281	298	302	329	342
$\lvert S^E\rvert / \lvert S^*\rvert$	0,0151	0,0098	0,0072	0,0063	0,0054	0,0047	0,0043	0,0038	0,0037	0,0034

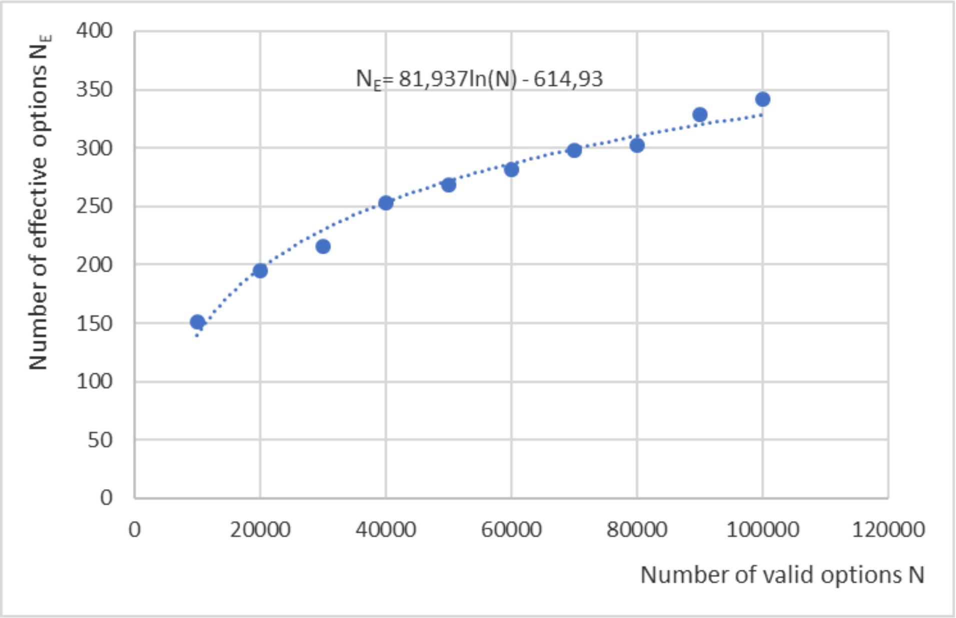

Fig. 3. Relative number of effective network options for $m=4$

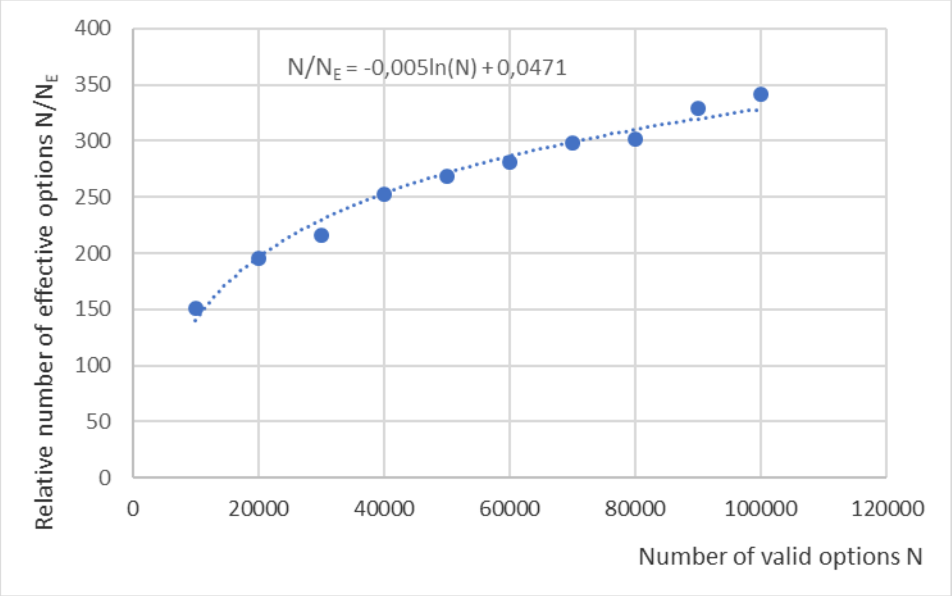

Fig. 4. Relative number of effective network options for $m = 4$

Based on the dimensionality of the network using the obtained approximation of the dependence of the power of the multiple number of effective options on the number of valid options (fig. 3), taking into account relation (16), we can choose the best method for solving the problem of its reengineering. This will allow to obtain the most effective options for reengineering of logistics networks, taking into account the available time and computing resources involved in design automation systems.

Conclusions

In the framework of the methodology of the system approach, closed logistics networks are considered as typical territorially distributed objects, the design tasks of which are combinatorial in nature and are solved by a variety of cost and functional indicators in conditions of incomplete certainty of goals and data. Significant costs of creation and operation of logistics networks need a perfect methodology of their optimization. In order to expand the capabilities of existing models of the problem of optimization of logistics networks, their improvement is proposed. The decision of the problem is made with the use of methodology of aggregative-decomposition approach that allows to carry out its analysis on meta-, macro- and microlevels. The optimization procedures, defined in this way, have been formalized for the complexes of tasks, related to the main stages of the life cycles of networks. They allow to obtain and transform task descriptions with their subsequent aggregation to obtain the best option of network reengineering.

On this basis, to optimize the network at the stage of reengineering, an iterative logical scheme of reengineering is chosen, which allows to jointly solve the entire set of problems and cyclically refine the data for subsequent tasks by the results of the previous ones. A general mathematical model of the multi-criteria problem of reengineering of topological structures of centralized three-tier logistics networks by the indicators of reduced costs, cargo delivery time, reliability and survivability has been improved. In order to obtain scalar estimates for the set of characteristics, universal functions of general utility and utility of local criteria are used. Excluding a part of local criteria and restrictions from the general model, it is possible to obtain models of all practically interesting problems of optimization of logistic networks. The models are proposed to be used in a combined method of options ranking for the final choice by a decision maker. This method, unlike traditional ones, implies formation rather than allocation of a subset of effective options, parametric synthesis of the general utility function and ranking of options according to the results of quantitative assessment. The developed complex of mathematical models extends methodological bases of automation of processes of optimization of logistic networks, allows to carry out correct reduction of a set of effective variants of their construction for a final choice taking into account knowledge and experience of designers that are difficult to formalize. Practical use of the offered complex of mathematical models will allow to lower time and capacity complexity of technologies of support of acceptance of design decisions, and at the expense of use of the offered procedures of selection of variants - to raise their quality on a set of functional and cost parameters. Further research in this direction can be directed at taking into account in the models of optimization of logistic networks the incomplete certainty of goals and input data, using the apparatus of interval or fuzzy analysis, as well as the development of more effective methods for their optimization.

References

1. Horbenko, I. D., Horbenko, Yu. I. (2012), *Applied cryptology: monograph* [*Prykladna kryptolohiia: monohrafiia*], Kharkiv: Kharkiv National University of Radio Electronics, LLC "Fort", 868 p.

2. Bevz, O. M., Kvєtnii, R. N. (2010), *Data Encryption Based on Highly Nonlinear Boolean Functions and Maximum Distance Codes:* monograph [*Shyfruvannia danykh na osnovi vysoko neliniinykh bulevykh funktsii ta kodiv z maksymalnoiu vidstanniu*: monohrafiia], Vinnytsia: Vinnytsia National University of Technology, 96 p.
3. Manifavas, C., Hatzivasilis, G., Fysarakis, K., Rantos, K. (2012), "Lightweight cryptography for embedded systems a comparative analysis", *In: 6th International Workshop on Autonomous and Spontaneous Security SETOP 2012, Springer, LNCS, 8247,* P. 333–349. DOI: https://doi.org/10.1007/978-3-642-54568-9_21
4. Gildas Avoine, Julio Hernandez-Castro (2021), "Security of Ubiquitous Computing Systems", *Selected Topics. Springer,* P. 265 DOI: https://doi.org/10.1007/978-3-030-10591-4
5. Biryukov Alex and Perrin Leo (2017), "State of the art in lightweight symmetric cryptography", *Cryptology ePrint Archive, Report 2017/511,* available at: http://eprint.iacr.org/2017/511, https://eprint.iacr.org/2017/511.pdf
6. Mitsuru Matsui (1997), "New block encryption algorithm MISTYC", *In Eli Biham, editor, Fast Software Encryption – FSE'97, pringer, volume 1267 of Lecture Notes in Computer Science, Haifa, Israel, January 20–22,* P. 54–68, available at: https://link.springer.com/chapter/10.1007/BFb0052334
7. Hatzivasilis George, Fysarakis Konstantinos, Ioannis (2018), "Papaefstathiou, and Charalampos Manifavas. A review of lightweight block ciphers", *Cryptographic Engineering,* No. 8 (2), P. 141–184. DOI: https://doi.org/10.1007/s13389-017-0160-y
8. Kerry A. McKay, Larry Bassham, Meltem Sonmez Turan, and Nicky Mouha (2016), "Nistir 8114 - report on lightweight cryptography". DOI: https://doi.org/10.6028/NIST.IR.8114
9. Rudnytsky, V. M., Lada, N. V., Babenko, V. G. (2018), *Cryptographic coding: synthesis of stream encryption operations with accuracy to permutation: monograph* [*Kryptohrafichne koduvannia: syntez operatsii potokovoho shyfruvannia z tochnistiu do perestanovky: monohrafiia*], Monograph, Kharkiv: LLC "DISA PLUS", 184 p.
10. Rudnitsky, V. M., Milchevich, V. Ya., Babenko, V. G., Melnyk, R. P., Rudnitsky, S. V., Melnyk O. G. (2014), *Cryptographic coding: methods and means of implementation (part 2):* monograph [*Kriptograficheskoe kodirovanie: metody i sredstva realizacii (chast' 2):* monografiya], Monograph, Kharkov: Publishing house "Shchedra sadyba plius", 223p.
11. Rudnytsky, V. M., ed. (2018), *Cryptographic coding: information processing and protection: collective monograph* [*Kryptohrafichne koduvannia: obrobka ta zakhyst informatsii: kolektyvna monohrafiia*], Monograph, Kharkiv: LLC "DISA PLUS", 139p.
12. Sysoienko, S., Myronets, I., Babenko, V. (2019), "Practical Implementation Effectiveness of the Speed Increasing Method of Group Matrix Cryptographic Transformation", *Proceedings of the Second International Workshop on Computer Modeling and Intelligent Systems (CMIS-2019), CEUR Workshop Proceedings 2353, CEUR-WS.org,* P. 402–412. (Scopus) available at: http://ceur-ws.org/Vol-2353/, http://ceur-ws.org/Vol-2353/paper32.pdf
13. Rudnitsky, V., Berdibayev, R., Breus, R., Lada, N. and Pustovit, M. (2019), "Synthesis of reverse two-bit dual-operated strictly straight cryptographic coding on the basis of another operation", *Advanced Information Systems, Kharkiv: NTU "KhPI",* No. 3 (4), P. 109–114. DOI: http://doi.org/10.20998/2522-9052.2019.4.16
14. Lada, N. V., Kozlovska, S. G., Rudnitsky, S. V. (2019), " The symmetric operations' mathematical group constructing based on module-2 addition " ["Pobudova matematy`chnoyi grupy` sy`metry`chny`x operacij na osnovi dodavannya za modulem dva"]. *Modern special technics: scientific and practical journal. Kyiv,* No 4 (59), P.33–41.
15. Lada, N. V., Kozlovska, S. G. and Rudnitskaya, Y. V. (2019), "Researching and Synthesizing a Group of Symmetric Modified Modulo-4 Addition Operations" ["Doslidzhennia i syntez hrupy symetrychnykh modyfikovanykh operatsii dodavannia za modulem chotyry "], *Central Ukrainian Scientific Bulletin. Technical Sciences,* No. 2 (33), P. 181–189. DOI: http://doi.org/10.32515/2664-262x. 2019.2(33)
16. Lada, N. V., Rudnitsky, S. V., Zazhoma, V. M. and Rudnytska, Y. V. (2020), " Research and synthesis of a group of symmetric modified operations of right-handed addition by module four" ["Doslidzhennia i syntez hrupy symetrychnykh modyfikovanykh operatsii pravostoronnoho dodavannia za modulem chotyry"], *Control, Navigation and Communication Systems. Academic Journal. Poltava: PNTU,* No. 1 (59), P. 93–96. DOI: https://doi.org/10.26906/SUNZ.2020.1.093
17. Rudnitsky, V. M., Babenko, V. G., Rudnitsky, S. V. (2012), " Method of synthesis of matrix models of operations of cryptographic recoding of information" ["Metod syntezu matrychnykh modelei operatsii kryptohrafichnoho perekoduvannia informatsii"], *Ukrainian Information Security Research Journal,* Vol 14, No. 3 (56), P. 50–56. DOI: https://doi.org/10.18372/2410-7840.14.3360

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ФОРМАЛІЗАЦІЯ ПРОБЛЕМИ ОПТИМІЗАЦІЇ МЕРЕЖ ТРАНСПОРТНОЇ ЛОГІСТИКИ НА ЕТАПІ РЕІНЖИНІРИНГУ

Предметом дослідження в статті є процес підтримки прийняття рішень в задачах оптимізації замкнених логістичних мереж на етапі реінжинірингу. **Мета** роботи – підвищення ефективності технологій автоматизованого проектування замкнених логістичних мереж за рахунок удосконалення математичних моделей багатокритеріальних задач реінжинірингу їх топологічних структур. У статті вирішуються наступні **завдання:** огляд і аналіз сучасного стану проблеми підтримки прийняття рішень в задачах оптимізації логістичних мереж на етапі їх реінжинірингу; декомпозиція проблеми оптимізації логістичних мереж на основних етапах їх життєвих циклів; вибір логічної схеми процесу реінжинірингу логістичної мережі як територіально розподіленого об'єкта; розробка математичної моделі загальної задачі багатокритеріальної оптимізації логістичних мереж за показниками економічності, оперативності, надійності та живучості; вибір моделей для скалярного багатокритеріального оцінювання варіантів реінжинірингу з урахуванням факторів, що важко піддаються формалізації, знань і досвіду особи, що приймає рішення. Використовуються такі методи: системний підхід, теорії систем, теорії корисності, теорії прийняття рішень, системного проєктування, оптимізації та дослідження операцій. **Результати.** Виконана декомпозиція проблеми реінжинірингу на задачі: визначення мети реінжинірингу та принципів перебудови мережі; оптимізації структури мережі; оптимізації топології елементів мережі; вибору технології функціонування; визначення параметрів елементів і транспортних засобів; оцінки та вибору найкращого варіанту побудови мережі. Удосконалено загальну математичну модель багатокритеріальної задачі реінжинірингу топологічних структур централізованих трирівневих логістичних мереж за показниками наведених витрат, часу доставки вантажів, надійності та живучості. Для отримання скалярних оцінок за множиною показників запропоновано універсальні функції загальної корисності і корисності локальних критеріїв. Виключення частини локальних критеріїв та обмежень із загальної моделі дозволяє отримувати моделі всіх практично цікавих задач оптимізації логістичних мереж. **Висновки.** Розроблений комплекс математичних моделей розширює методологічні засади автоматизації процесів проєктування логістичних мереж, дозволяє здійснювати коректне скорочення множини ефективних варіантів їх побудови для остаточного вибору з урахуванням факторів, що важко піддаються формалізації, знань і досвіду проєктувальників. Практичне використання запропонованого комплексу математичних моделей дозволить знизити часову й ємнісну складності технологій підтримки прийняття проєктних рішень, а за рахунок використання запропонованих процедур відбору варіантів – підвищити їх якість за множиною функціональних і витратних показників.

Ключові слова: логістична мережа; технологія проєктування; оптимізація; реінжиніринг; багатокритеріальне оцінювання; підтримка прийняття рішень.

ФОРМАЛИЗАЦИЯ ПРОБЛЕМЫ ОПТИМИЗАЦИИ СЕТЕЙ ТРАНСПОРТНОЙ ЛОГИСТИКИ НА ЭТАПЕ РЕИНЖИНИРИНГА

Предметом исследования в статье является процесс поддержки принятия решений в задачах оптимизации замкнутых логистических сетей на этапе реинжиниринга. **Цель** работы – повышение эффективности технологий автоматизированного проектирования замкнутых логистических сетей за счет усовершенствования математических моделей многокритериальных задач реинжиниринга их топологических структур. В статье решаются следующие **задачи:** обзор и анализ современного состояния проблемы поддержки принятия решений в задачках оптимизации логистических сетей на этапе их реинжиниринга; декомпозиции проблемы оптимизации логистических сетей на основных этапах их жизненных циклов; выбор логической схемы процесса реинжиниринга логистической сети как территориально распределенного объекта; разработка математической модели общей задачи многокритериальной оптимизации логистических сетей по показателям экономичности, оперативности, надежности и живучести; выбор моделей для скалярной многокритериальной оценки вариантов реинжиниринга с учетом трудноформализуемых факторов, знаний и опыта лица, принимающего решения. Используются следующие **методы:** системный подход, теории систем, теории полезности, теории принятия решений, системного проектирования, оптимизации и исследования операций. **Результаты.** Выполнена декомпозиция проблемы реинжиниринга на задачи: определения цели реинжиниринга и принципов перестройки сети; оптимизации структуры сети; оптимизации топологии элементов сети; выбора технологии функционирования; определения параметров элементов и транспортных средств; оценки и выбора наилучшего варианта построения сети Усовершенствована общая математическая модель многокритериальной задачи реинжиниринга топологических структур централизованных трехуровневых логистических сетей по показателям приведенных затрат, времени доставки грузов, надежности и живучести. Для получения скалярных оценок по множеству показателей предложены универсальные функции общей полезности и полезности локальных критериев. Исключение части локальных критериев и ограничений из общей модели позволяет получать модели всех практически интересных задач оптимизации логистических сетей. **Выводы.** Разработанный комплекс математических моделей расширяет методологические основы автоматизации процессов проектирования логистических сетей, позволяет осуществлять корректное сокращение множества эффективных вариантов их построения для окончательного выбора с учетом трудно поддающихся формализации знаний и опыта проектировщиков. Практическое использование предлагаемого комплекса математических моделей позволит снизить временную и емкостную сложности технологий поддержки принятия проектных решений, а за счет использования предложенных процедур отбора вариантов – повысить их качество по множеству функциональных и затратных показателей.

Ключевые слова: логистическая сеть; технология проектирования; оптимизация; реинжиниринг; многокритериальная оценка; поддержка принятия решений.

Бібліографічні описи / Bibliographic descriptions

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