UDC 004.9: 519.81 **doi:** https://doi.org/10.20998/2522-9052.2025.4.06

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ADAPTATION OF LOGISTICS NETWORK STRUCTURES IN EMERGENCY SITUATIONS

Abstract. The **subject** of research in the article is the process of adapting topological structures of micrologistics networks under the negative influence of the external environment. The **goal** of the work is increasing the efficiency of technologies for rapid adaptation of logistics networks (LN) to the negative impacts of emergency situations by developing a mathematical model of their multi-criteria optimization under conditions of incomplete uncertainty of input data. **The following tasks are solved in the article:** analysis of the current state of the optimization problem in adapting topological network structures to the negative impacts of emergency situations; development of problem statements for rapid adaptation of topological network structures to the negative impacts of emergency situations; formalization of indicators for evaluating options for adapting LN structures to the negative impacts of emergency situations; development of mathematical models of multi-criteria optimization problems of topological structures under conditions of incomplete uncertainty of input data; development of an algorithm for comparing network construction options for interval-based input data. The following **methods** are used: systems theory, utility theory, combinatorial optimization, operations research, interval and fuzzy mathematics. **Results.** To achieve the goal, the formulation of tasks for rapid adaptation and reengineering of topological structures of networks to the negative impacts of emergency situations was developed; the formalization of indicators for evaluating options for adapting topological structures of networks to the negative impacts of emergency situations was performed; mathematical models of optimization problems of topological structures under conditions of incomplete uncertainty of input data were developed according to the indicators of the given costs, efficiency and time of network adaptation. An algorithm for comparing network construction options according to local and generalized criteria for interval-based estimates was proposed. **Conclusions.** According to the results of the study, a solution to the scientific and practical problem of increasing the efficiency of technologies for rapid adaptation of networks to the negative effects of emergencies is proposed by developing a mathematical model of their multi-criteria optimization under conditions of interval certainty of input data. The results obtained expand the methodological principles of automation of processes supporting the adoption of multi-criteria design decisions when designing and adapting topological structures of micrologistics networks. They allow obtaining effective solutions to the problems of the fastest possible restoration of supply using the means that remained after the onset of an emergency and subsequent reengineering of the network construction option. The practical use of the results obtained will allow reducing the time for restoration of supply in the event of damage to elements and infrastructure of logistics networks, and by using the technology of selecting subsets of effective options with interval-specified characteristics, guaranteeing the quality of design solutions and providing their more complete assessments.

Keywords: logistics network; topological structure; adaptation; mathematical model; decision making; multi-criteria optimization; interval analysis; utility theory.

Introduction

The effectiveness of anthropogenic objects used in various spheres of human activity is largely determined by the quality of the corresponding logistics [1–3]. At the same time, even in the absence of emergencies, logistics networks (LN) operate in conditions of constant changes in the nomenclature and volumes of supplies, multiple senders and recipients of goods, the size of the territory served, environmental restrictions, etc. At a certain stage, existing supply networks become ineffective. Attempts to adapt LN by solving traditional optimization problems do not guarantee effective options for their construction. The reason is the need to take into account the topology of existing terminals and the possibility of using their equipment in the construction options of the networks being created. To take these factors into account, it is advisable to use network reengineering technologies, which involve a fundamental analysis of existing construction options (types of transport, structure, topology, parameters, technology) and radical redesign [4]. In the process of systematic reengineering of LN, it is necessary to solve a set of tasks of structural, parametric, and topological optimization, taking into account the connections between the variants of their construction at all stages of their life cycles [5]. At the same time, it is known that the most difficult from a computational point of view are the tasks of optimizing the structure and topology of networks [6].

In emergency situations (pandemics, tsunamis, volcanic eruptions, military operations, etc.), existing supply chains in such networks are disrupted, and new problems and risks arise that significantly affect the quality of logistics processes. At the same time, traditional tasks of designing and optimizing logistics networks become significantly more complicated [7]. In particular, along with the traditional tasks of optimizing the topological or functional structures of networks in terms of cost-effectiveness and speed of delivery, new tasks arise related to minimizing the time required to restore supplies, ensuring the necessary levels of reliability, survivability, etc. [8]. In practice, this is associated with significant changes in the structures, topology, parameters, and technologies of network operation [9]. Projects for the restoration, adaptation, or reengineering of logistics networks in emergency situations involve the development of action plans aimed at the rapid restructuring of supply chains to reduce dependence on changes in suppliers, hub networks, or individual routes [10]. At the same time, when conducting a comparative analysis of logistics technologies, multi-criteria evaluation methods are used [11, 12].

To obtain effective options for building networks or adapting their structures, it is considered expedient to jointly solve the problems of their structural, parametric, topological, and technological optimization based on a set of functional and cost indicators [13]. The vast majority of LN construction options generated during their design are Pareto inefficient [14]. In the process of network optimization, it is necessary to pre-select the Pareto front among them and reduce the set of effective options based on an analysis of the advantages between their quality indicators [15]. To evaluate the effectiveness of options from a set of acceptable ones, utility theory and modern methods of expert evaluation are used: fuzzy bipolar [16]; correlation of capabilities using fuzzy numbers [17]; fuzzy soft choice [18]; lexicographic optimization [19]. The quality of alternative options is assessed by computer modeling with a certain margin of error [20]. As a result, decisions on the best option for building or adapting a network are made in conditions of incomplete certainty of their assessments and the relationship between potential effects and the costs of achieving them. The use of fuzzy or interval mathematics methods for ranking options for adapting LN to emergency conditions or martial law, taking into account the incomplete certainty of input data, requires the formalization of operations for comparing assessments according to local and general efficiency criteria [21, 22].

Analysis of the current state of the issue

Nowadays, logistics activities are considered as a set of measures related to the formation of balanced ratios of material, information, financial, and other costs and cover a variety of stages of their circulation from an external source to the end consumer.

The work [23] presents the results of research on theoretical concepts, methods, and methodological approaches to managing the logistics activities of an enterprise and its procurement activities in particular, which lays the foundation for the development of network optimization tools.

To improve the efficiency of existing logistics processes, a variety of technologies have been developed to date, the main ones being automation, optimization, engineering, and reengineering.

The results of a comparative analysis of modern technologies for improving logistics processes are presented in Table 1 [24].

Table 1 – **Comparative analysis of tools for improving logistics processes [24]**

Tool name	Application objectives	Implementation principles	Similarities with reengineering
Automation	Accelerate delivery; reduce logistics costs through effective management of transport resources and reduction of fuel costs, vehicle fleet maintenance, insurance, and other operating expenses	Use of digital technologies to increase the speed and efficiency of logistics processes.	Time reduction, process efficiency improvement, safety, environmental friendliness, cost-effectiveness
Optimization	Improvement of various stages of the supply chain to minimize resource and time costs	Selection of optimal steps for implementing logistics processes (routes, suppliers, etc.)	Improvement of performance indicators, cost, time, quality, business process fragmentation
Engineering	Improvement of logistics business processes by designing business processes for newly created logistics systems or logistics chains, taking into account best practices and the principle of optimality	Building new logistics chains and processes	Preparation of production processes for normal production and product sales, redesign of logistics processes, combined in a single information field
Reengineerin g	Increasing the competitiveness of the enterprise, overcoming the crisis, improving management efficiency, improving, optimizing, engineering business processes, reorganization	Eliminating unnecessary and unproductive steps, automating and standardizing operations, introducing new technologies and innovations.	Reduction of costs, increase in labor productivity, increase in the speed of order and service fulfillment, improvement in product (service) quality, reduction in staff

The choice of technology for improving logistics processes depends on the objectives and available time, material, and financial resources.

At the present stage, conditions have been created for the transition to a strategy of innovative development of logistics, which creates opportunities for processing large amounts of data and expanding the prospects for using the information and analytical centers of logistics providers. When assessing the state and implementation of innovations, the World Bank's Logistics Performance Index is used, which is a unique benchmarking tool for a comprehensive assessment of logistics systems [1].

In the absence of emergencies in stable conditions, existing LM can maintain the efficiency of their structures for a certain period of time. Natural disasters, accidents, pandemics, and military actions cause obstacles or interruptions in logistics processes and can significantly affect the reliability and delivery times of goods.

Work [8] examines the problem of designing a logistics network in emergency situations with shared use of resources. To optimize vehicle routes, a two-objective model of mixed integer programming is proposed based on cost and emergency response speed indicators.

The problem of designing a humanitarian aid LM in emergency situations using the robust-fuzzy-probabilistic planning method is considered in [25], which proposes a solution for the optimal location of aid distribution centers, determining the optimal amount of goods stored in them, and distributing goods and victims between supply facilities.

The issue of optimizing the location of resources and routing in emergency logistics after earthquakes is discussed in [26]. It proposes a solution to reduce social costs and risks for the logistics network by determining the best locations for distribution centers, optimal strategies for distributing emergency materials, and plans for loading materials.

The results of research into problems in logistics process management systems in Ukraine and proposals for their solution under martial law are presented in [7]. When optimizing logistics processes, it is proposed to focus on: their planning (forecasting) and adjustment, taking into account security issues and risks [27]; regulating inventory management processes; diversifying supply options; forming critical resource volumes; adequately assessing the volumes of products that can be sold;

The work [9] highlights the key problems faced by enterprises in wartime and analyzes the impact of damage to the logistics infrastructure on the cost of deliveries. The proposed technology for adapting Ukrainian logistics infrastructure to unpredictable events involves four stages: market analysis and forecasting of possible changes (researching market trends, conditions, and forecasting possible changes in demand and supply conditions); adjustment of logistics processes (control and changes in delivery routes and storage technologies, search for new suppliers); control of stocks, their security and rationalization (refusal to accumulate and store excess goods in warehouses for long periods); identification of alternative supply options in cooperation with other suppliers.

In modern logistics, macro- and micro-logistics subsystems are distinguished [4]. Macro-logistics systems are used for the interaction of several property objects that are not related to the territorial distribution of suppliers and consumers. Micro-logistics systems are designed for the interaction of one or more enterprises with the same economic interests or a single enterprise [23]. In the transport micro-logistics of large companies, global and local transport systems are distinguished.

The traditional task of optimizing global transportation is to determine the best location for terminals to minimize transportation costs or induced costs [28]. Local transportation systems are used to deliver goods from global network recipients to end consumers. In these systems, cargo is delivered via a network of circular routes.

In the traditional task of optimizing a global transportation network, the following are considered given: the location of the supply center, a set of recipients $I = \{i:\ i = \overline{1,n}\}$, for each of which the location, supply volumes, and transportation tariffs for the delivery of goods are specified. It is necessary to determine the optimal number u^o and location of terminals and the subset of recipients served by each of them in terms of cost $I_j = \{i\},\ j = \overline{1,u^o}$

$$C = \sum_{j=1}^{n} c_j v_{jj} + \sum_{j=1}^{n}\sum_{i=1}^{n} d_{ji} v_{ji} \to \min_{v}, \qquad (1)$$

where c_j – the costs of creating and using the j-th terminal; v_{ij} – Boolean variable ($v_{ij} = 1$, if the i-th recipient is directly connected to the j-th terminal, $v_{ij} = 0$ – otherwise); d_{ji} – the expenses of delivering goods from the j-th terminal to the i-th recipient.

The subject of reverse logistics is the organization of reverse flows [29–30]. Conditionally independent solutions to direct and reverse logistics problems do not allow for effective solutions to logistics problems. Their joint solution generates a set of tasks for developing new mathematical models and effective methods for their study for closed logistics systems [6]. The task of structural and topological optimization of a centralized three-level closed LN is distinguished by the requirement to take into account reverse flows from recipients to collection centers (production, processing, or disposal). In this case, for a set of elements (recipients, supply centers, processing centers, terminals) with given characteristics, it is necessary to synthesize an effective structure in which the first level contains production and processing centers, the second level contains terminals, and the third level contains recipients.

The costs of a network with direct and reverse flows consist of the sum of the costs of delivering the direct flow from the supply center to the terminals C_{SN}, for processing in forward and reverse flow terminals C_{N1}, C_{N2}, for direct flow delivery from terminals to recipients C_{NC}, for the delivery of return flow from recipients to terminals C_{CN}, for the delivery of return flow from terminals to the processing center C_{NR}:

$$C = C_{SN} + C_{N1} + C_{NC} + C_{CN} + C_{N2} + C_{NR}. \qquad (2)$$

In the case of coinciding delivery and processing points, the objective function (2) for this task is presented in the following form [6]:

$$C(x) = \sum_{i=1}^{n} c_i x_{ii} + \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij} x_{ij} \to \min_{x}. \qquad (3)$$

where c_i – the costs incurred for the node formed on the basis of the i-th network element; x_{ij} – Boolean variable reflecting the presence of direct links between network elements; c_{ij} – the costs of delivering the flow from point i to point j.

The objective function (2), unlike (1), takes into account the costs of delivering both direct and reverse flows. The system of constraints that define the three-level centralized structure assumes that [6]:

– each recipient i, $i=\overline{1,n}$ must be connected to one of the network nodes: : $\sum_{j=1}^{i} s_{ij} + \sum_{i=j}^{n} s_{ij} = 1$ for all i, for which $s_{ii}=0$, $i=\overline{1,n}$ or directly to the center $s_{1i}=0$, $i=\overline{1,n}$;

– each node must be directly connected to at least one recipient $\sum_{j=1}^{i} s_{ij} + \sum_{i=j}^{n} s_{ij} = 1$, for all i, for which $s_{ii}=1$, $i=\overline{1,n}$;

– each recipient i connects to node j according to the minimum cost indicator:

$$s_{ii} \wedge s_{ij} = 1 \to ij = \arg \min_{1 \le i, j \le n} c_{ij} \quad \forall i, j = \overline{1,n};$$

– each of the nodes j must be directly connected to the center $s_{jj} = 1 \to s_{1j} = 1$, $\forall i, j = \overline{1,n}$;

– the total number of connections in the network

$$\sum_{j=1}^{n} \sum_{i=j}^{n} s_{ij} = n + \sum_{i=1}^{n} s_{ii} .$$

An important characteristic of logistics networks is efficiency, which reflects the time it takes to deliver goods from the center to recipients. In [4], a model of the LN structural-topological optimization problem is proposed, in which the quality of its reengineering options is evaluated based on the indicators of the given costs and efficiency. Given the desire to minimize the maximum delivery time of goods to recipients, the criterion for maximizing efficiency can be presented as:

$$\tau(s) = \tau_{SN}(s) + \tau_N(s) + \tau_{NC}(s) \to \min_{s \in S}, \qquad (4)$$

where $\tau_{SN}(s)$ – the time of transportation of goods from the center to the most distant terminal; $\tau_N(s)$ – the maximum time for processing goods at the terminal; $\tau_{NC}(s)$ is the maximum time for delivery of cargo from the terminal to the recipient; S is the set of acceptable options for network reengineering.

Determining the set of acceptable LN $S = S^U \setminus \overline{S}$ options consists of removing from the universal set S^U a subset of options $\overline{S}$ that do not meet financial $C(s) \le C*$ or time $\tau(s) \le \tau*$ constraints (where $C*$ and $\tau*$ are acceptable values for costs and delivery time) [15]. The best option for building a network is selected from the set of efficient (Pareto-optimal) options. The procedure for selecting a subset of efficient LN construction options $S^E \subset S$ consists of removing from the set $S \subset S^U$ of admissible options a subset of inefficient options $\overline{S}^E \subset S$. In this case, an option $s^E \in S^E$ is called efficient if there is no option in the set S of acceptable options for which the inequalities $C(s) \le C(s^E)$ and $\tau(s) \le \tau(s^E)$ would be true and at least one of them would be strict [15]. For this purpose, methods of pairwise comparisons are used, based on Karlin's lemma, based on Hermeier's theorem, evolutionary search [14].

The ranking of LN construction options and the selection of the best among them $s^o \in S^E$ is carried out on the set of effective options by maximizing their utility using the relative priority scale [29], of the hierarchy analysis method [32], the ELECTRE family of methods [33], the PROMETHEE-GAIA methodology [34], TOPSIS, VIKOR, SIR [35].

In a two-criteria problem, the option is selected based on a generalized indicator [36]:

$$s^o = \arg \max_{s \in S} P(s) . \qquad (5)$$

As a generalized assessment of the effectiveness of the reengineering option $P(s)$ in (5), it is proposed to use the membership function of the fuzzy set “Best option”:

$$\text{«Best option»} = \{< s, P(s) >, \qquad (6)$$

where $s \in S$ is the network construction option specified by a Boolean matrix; $P(s)$ is the value of the total utility function of the option, which evaluates the degree of its membership in the fuzzy set (6).

Statement of research goals and objectives

Recent years have clearly demonstrated that emergencies, pandemics, and military actions create unpredictable challenges for existing logistics processes. In particular, such conditions pose threats to employee safety, can cause extensive damage to terminals and transport infrastructure, and lead to significant instability or complete disruption of supplies. In order to avoid undesirable consequences, strategies for continuous analysis and adaptation of LN are implemented, which contributes to ensuring their uninterrupted and efficient functioning. To implement the strategy of adapting LN to external challenges, existing and new means of improving supply networks, reducing risks, and increasing the efficiency of logistics technologies are used.

Based on the results of a review and analysis of the current state of the problem of optimizing the topological structures of logistics networks, it has been established that [1-36]:

– the vast majority of LN optimization tasks are multi-criteria and combinatorial in nature;

– input data is determined on the basis of forecast estimates, and the evaluation of the functional and cost characteristics of LN construction options is carried out using analytical or simulation modeling with some errors;

– fuzzy or interval mathematics methods are used to account for the incomplete certainty of the parameters of LN optimization task models. The use of fuzzy sets is only possible in cases where the parameters or variables are defined on the same universes. With interval data representation, it is problematic to compare the characteristics of LN;

– the process of selecting the best solution for organizing LN is carried out by the decision maker (DM) from among a small number of effective options;

– existing mathematical models and methods for optimizing global transportation LNs do not allow solving problems with regard to their rapid adaptation to the negative effects of external influences.

This determines the relevance of scientific and practical tasks of developing effective mathematical models and methods for solving multi-criteria problems of rapid adaptation of logistics networks in conditions of incomplete uncertainty of input data.

The aim of the study is to improve the effectiveness of technologies for the rapid adaptation of LN to the negative effects of emergencies by developing a mathematical model for their multi-criteria optimization in conditions of incomplete uncertainty of input data.

The object of the study is micro-logistics networks in conditions of negative external environmental influences.

The subject of the study is the process of adapting the topological structures of micro-logistics networks in conditions of negative environmental impact.

To achieve the goal, the following tasks are to be solved:

– development of tasks for the rapid adaptation of network topological structures to the negative effects of emergency situations;

– formalization of indicators for evaluating options for adapting LN structures to the negative effects of emergency situations;

– development of mathematical models for multi-criteria optimization of topological structures in conditions of incomplete uncertainty of input data;

– development of an algorithm for comparing options for building networks for interval-presented input data.

Statement of tasks for adapting the topological structure of the network

The paper considers one of the most common three-level micro-logistics networks in practice. Its structural elements are: the cargo dispatch center *F*; a set of terminals *T* that receive cargo from the center; and a subset of cargo recipients *C*. The dispatch center *F*, terminals *T*, and recipients *C* are connected to each other by a centralized supply scheme.

The general task of adapting the topological structure of a network that has been damaged as a result of emergencies involves solving conditionally independent tasks for global networks Pr_1 and local transport networks Pr_2.

The adaptation of global transport networks Pr_1 is carried out by solving two problems:

– the fastest possible restoration of temporary supply using the resources (terminal areas and equipment, roads, vehicles) that have survived after the emergency Pr_{11};

– reengineering the network construction option with the possibility of using the resources that remained after the emergency Pr_{12}.

The task of restoring temporary supply as quickly as possible Pr_{11} is proposed to be considered in the following terms.

Given: a set of elements of the base network (dispatching center *F*, terminals *T* and recipients *C*), routes that remained intact after the emergency Pr_{11}; transportation and handling costs at terminals.

It is necessary to determine the option for connecting receivers to the surviving terminals at the lowest cost of cargo delivery. The task of reengineering the network construction option Pr_{12} is proposed to be considered in the following formulation.

Given: the initial set of network elements; the option of its topological structure that existed before the emergency, represented by the locations of the center *F*, terminals *T* and receivers *C*, connections between the center, terminals and receivers; the costs of creating (modernizing) and operating terminals, implementing transportation, the cost of resources that can be reused (or sold) after dismantling terminal equipment or vehicles; the time required to restore or create a new terminal.

It is necessary to determine the best option for the topological structure of the logistics network, evaluating it in terms of network recovery time, cargo delivery time, and the above costs.

The tasks of adapting the local transport network Pr_2 boil down to the tasks of several traveling salesmen with constraints (MTSPC – Multiple TSP with Constraint).

Formalization of indicators for evaluating structural adaptation options

In emergency situations, some elements and transport infrastructure of the LN may be disabled. At the first stage, it is necessary to restore temporary cargo delivery to terminals and recipients as quickly as possible using the surviving elements of the network infrastructure. The goal of problem Pr_{11} is to find a network configuration for delivering cargo to recipients by connecting them to the surviving terminals *T* at minimum cost. Given the incomplete certainty of the input data (supply volumes, costs, transportation speed, etc.), we will present them in intervals of the form $[w_i] \in [w_i^-; w_i^+]$, $i = \overline{1, n_D}$ (where n_D – number of input data types). Variables in target functions for different network $s \in S$ construction options (where S – multiple acceptable network construction options) will be presented as interval values $[x_i(s)] \in [x_i^-(s); x_i^+(s)]$, $i = \overline{1, n_V}$ (where n_V – number of variables). Values of local criteria characterizing the quality of the LN $s \in S$ construction variant we will denote $[k_j(s)] = [k_j^-(s); k_j^+(s)]$, $j = \overline{1, m}$ (where m – number of local criteria) [36]. When forming the objective function of the task Pr_{11}, we will use the following notation: $I = \{i : i = \overline{1, n}\}$ – set of network elements (center, terminals, receivers); $s' = [s'_{ij}]$, $i, j = \overline{1, n}$ – adjacency matrix of the preserved network topology ($s'_{ij} = 1$), if there is a direct connection between elements *i* and *j* and $s'_{ij} = 0$ – otherwise; $i = 1$ – corresponds to the center; $s'_{ii} = 1$ $\forall i = \overline{1, n}$ – if a terminal is formed on the basis of the i-th element); $[c_i] = [c_i^-; c_i^+]$, $i = \overline{1, n}$ – interval representation of the given costs of operating the *i*-th terminal; $[c_{ij}] = [c_{ij}^-; c_{ij}^+]$, $i, j = \overline{1, n}$ – interval representation of the costs of transportation between elements i and j; S – set of permissible network construction options.

Using the introduced designations, it is proposed to represent the objective function of interval-represented costs for this problem in the following form:

$$[k_1(s', s)] = [C(s', s)] = \\ = \sum_{i=1}^{n} [c_i] s_{ii} + \sum_{i=1}^{n} \sum_{j=1}^{n} [c_{ij}] s_{ij} \to \min_{s \in S}. \quad (7)$$

The time interval for delivery of cargo to the i-th recipient consists of the time for delivery from the center to the corresponding j-th terminal $[t_{1j}(s)]$, processing of cargo there $[t_j(s)]$, and delivery from the j-th terminal to the i-th recipient $[t_{ji}(s)]$. Given the desire to minimize the maximum delivery time of cargo to recipients, the target function of interval-presented efficiency is proposed to be presented in the form [36]:

$$[k_2(s', s)] = \max_{1 \le i \le n} \{ \sum_{j=1}^{n} \left\{ \begin{matrix} [t_{1j}(s)] + [t_j(s)] + \\ + [t_{ji}(s)] \} s_{ji} \end{matrix} \right\} \to \min_{s \in S}. \quad (8)$$

At the second stage, it is necessary to solve the problem of network reengineering with the possibility of using the surviving infrastructure elements s' and taking into account the additional criterion of time for its restoration $k_3(s', s) = \tau(s', s)$.

As an indicator of efficiency, we will use the intervals of the above costs for the network option adapted according to the results of reengineering:

$$[k_1(s', s)] = C[s] = \\ = \sum_{j=1}^{n} \left\{ \begin{matrix} [a_j](1 - s'_{jj}) s_{jj} + [b_j] s'_{jj} s_{jj} + \\ [c_j](1 - s_{jj}) s'_{jj} - [d_j](1 - s_{jj}) s'_{jj} \end{matrix} \right\} + \\ + \sum_{j=1}^{n} \sum_{i=j}^{n} [e_{ji}] s_{ji} \to \min_{s \in S}, \quad (9)$$

where $[a_j]$, $[b_j]$, $[c_j]$, $[d_j]$, $j = \overline{1, n}$ – intervals of costs for creation, modernization, dismantling, and the cost of resources that can be reused after dismantling the equipment of the j-th terminal in the new structure; $[e_{ij}]$ – intervals of costs for transporting goods from the j-th terminal to the i-th recipient, $i, j = \overline{1, n}$. Taking into account one type of structure for estimating the delivery time of cargo in this task, the ratio (8) can also be used.

In this task, it is also necessary to minimize the total time for adapting the supply network $[\tau(s', s)]$, which consists of the time for construction or restoration of terminals $[\tau_j(s)]$ and routes between terminals and recipients $[\tau_{ij}(s)]$:

$$[k_3(s', s)] = [\tau(s', s)] = \\ = \sum_{j=1}^{n} [\tau_j] \cdot s_{jj} + \sum_{j=1}^{n} \sum_{i=j}^{n} [\tau_{ji}] \cdot s_{ji} \to \min_{s \in S}. \quad (10)$$

Depending on external conditions and the defined goal of network adaptation, various restrictions and preferences for target functions (7) – (10) may be established in practice.

Mathematical models of structural adaptation problems

The tasks of restoring supply as quickly as possible following an emergency situation Pr_{11} and reengineering network construction options Pr_{12} can be solved in practice using different combinations of local criteria under various quality constraints.

The basic system of constraints defines a given type of centralized three-level structure:

– each recipient must be connected to one of the network nodes;

– at least one recipient must be directly connected to each terminal;

– each terminal must be directly connected to the center;

– each receiver connects to the terminal based on the minimum delivery cost.

The generalized form of the multi-criteria problem of adapting LN topological structures can be presented as follows:

$$\begin{cases} [k_1(s', s)] \to \min_{s \in S}, \; k_1(s', s)] \le k_1^*, \\ [k_2(s', s)] \to \min_{s \in S}, \; [k_2(s)] \le k_2^*, \\ [k_3(s', s)] \to \min_{s \in S}, \; [k_3(s)] \le k_3^*, \end{cases} \quad (11)$$

$$S = \{s\} = \\ = \begin{cases} [s_{ij}], \; s_{ij} \in \{0,1\}, \; i, j = \overline{1, n}, \; s_{11} = 1; \\ \sum_{i=j}^{n} s_{ij} \ge 1, \; \forall j = \overline{1, n}; \\ \sum_{j=1}^{n} \sum_{i=j}^{n} s_{ij} = n + \sum_{i=1}^{n} s_{ii}; \\ s_{ii} = 1 \to s_{i1} = 1 \; \forall i = \overline{1, n}; \\ s_{ii} \wedge s_{ij} = 1 \to ij = \arg \min_{1 \le i, j \le n} [e_{ij}] \; \forall i, j = \overline{1, n}, \end{cases} \quad (12)$$

where k_1^*, k_2^*, k_3^* – maximum permissible values of indicators of cost, efficiency, and time required for structure adaptation.

By changing the number of local criteria and the values of restrictions on the maximum permissible values of indicators of cost, efficiency, and time required for adaptation, it is possible to obtain all the options for adapting LN topological structures that are important in practice.

To compare options $s \in S$ when solving the problems under consideration, generalized values $[P(s)]$ of their value are used, which determine their ordering:

$$\begin{cases} \{\forall s, v \in S : s \succ v \leftrightarrow [P(s)] > [P(v)]; \\ s \succsim v \leftrightarrow [P(s)] \ge [P(v)]; \\ s \sim v \leftrightarrow [P(s)] = [P(v)]. \end{cases} \quad (13)$$

In conditions of interval determination of input data, it is proposed to select the adaptation option based on a generalized indicator [36]:

$$s^o = \arg\max_{s \in S^*} [P(s)], \quad (14)$$

$$[P(s)] = \sum_{i=1}^{3} \lambda_i [\xi_i(s)] + \sum_{i=1}^{3}\sum_{j=i}^{3} \lambda_{ij} [\xi_i(s)][\xi_j(s)] + ..., \quad (15)$$

where λ_i, λ_{ij} – weight coefficients of local criteria and their products $\lambda_i \ge 0$, $\lambda_{ij} \ge 0$; $\xi_l(s)$ – utility function of the local criterion $k_l(s)$, $l = i, j$.

For the convenience of practical use of the model in network optimization tasks, it is proposed to perform a convolution of local criteria. Depending on the available information, a linear or universal glue function can be used to normalize the values of local criteria [21]:

$$\xi_j(s) = \begin{cases} \bar{a}_j (b_{j1}+1)\left(1-\left(b_{j1} / \left(b_{j1} + \bar{k}_j(s) / \bar{k}_{ja}\right)\right)\right), \\ \qquad 0 \le \bar{k}_j(s) \le \bar{k}_{ja}; \\ \left(1-\left(b_{j2} / \left(b_{j2} + \dfrac{\overline{k_j}(s) - \bar{k}_{ja}}{1-\bar{k}_{ja}}\right)\right)\right) \times \\ \times \overline{a_j} + (1-\overline{a_j})(b_{j2}+1), \bar{k}_{ja} < \bar{k}_j(s) \le 1, \end{cases} \quad (16)$$

where b_{j1}, b_{j2} – parameters determining the type of dependencies (13) at the initial and final segments of the function; $\bar{k}_{ja}, \bar{a}_j$ – normalized values of the coordinates of the points of the function's gluing, $0 \le \bar{k}_{ja} \le 1$, $0 \le \bar{a}_j \le 1$; $\bar{k}_j(s) = [k_j(s) - k_j^-]/(k_j^+ - k_j^-)$ – normalized value of the j-th criterion for the variant s.

Algorithm for comparing network construction options for interval-valued input data

Ranking of LN adaptation options and selection of the best $s^o \in S$ among them is carried out on a set of effective ones [37] according to the maximum value of their utility [38]. To compare the interval-defined values of local criteria $[k_j(s)]$, $j = \overline{1,m}$ and the generalized criterion $[P(s)]$ (15), it is proposed to use the apparatus of interval mathematics [39, 40]. It is proposed to compare non-intersecting interval estimates by comparing their centers (mean values) [41]. If the intervals of estimates intersect, the selection of the best among them will be determined by their mutual location [42]. To compare intersecting intervals of estimates, we will use the Hukuhara generalized difference estimate $A \overset{-}{_{gH}} B$ and the comparison index $\gamma_{A,B}$, which determines the ratio between hypothetical gains and losses based on the results of the selection [43]. The proposed algorithm for comparing network construction options for interval-represented input data involves the following steps.

1. Start.

2. Input for options $s_i, s_l \in S$ of interval-defined values of utility functions of local criteria $A = [\xi_j^-(s_i); \xi_j^+(s_i)]$ and $B = [\xi_j^-(s_l); \xi_j^+(s_l)]$, $j = \overline{1,m}$ or generalized efficiency criterion (15).

3. Calculation of centers $\hat{a}$, $\hat{b}$, radii $\bar{a}$, $\bar{b}$ and intervals A and B.

4. Calculation for intervals A and B and values of the generalized Hukuhara difference and index $I(A,B)$.

5. If $\hat{a} > \hat{b}$, $a^- < b^-$ and $I(A,B) < 0$, then $A \succ B$, otherwise $A \prec B$; go to p. 9.

6. If $\hat{a} > \hat{b}$, $a^- \ge b^-$ and $I(A,B) > 0$, then $A \succ B$, otherwise $A \prec B$; go to p. 9.

7. If $\hat{a} > \hat{b}$, $a^+ < b^+$ and $I(A,B) < 0$, then $A \succ B$, otherwise $A \prec B$; go to p. 9.

8. If $\hat{a} > \hat{b}$, $a^+ \ge b^+$ and $I(A,B) > 0$, then $A \succ B$, otherwise $A \prec B$; go to p. 9.

9. End.

For interval values $a \in [a^-; a^+]$ and $b \in [b^-; b^+]$ rules for performing basic interval arithmetic operations are presented in the following form [41]:

$$[a] + [b] = [a^- + b^-; a^+ + b^+], \quad (17)$$

$$[a] - [b] = [a^- - b^+; a^+ - b^-], \quad (18)$$

$$[a]\cdot[b] = \begin{bmatrix} \min\{a^- \cdot b^-, a^- \cdot b^+, a^+ \cdot b^-, a^+ \cdot b^+\}; \\ \max\{a^- \cdot b^-, a^- \cdot b^+, a^+ \cdot b^-, a^+ \cdot b^+\} \end{bmatrix}, \quad (19)$$

$$[a]/[b] = [1/b^+; 1/b^-], \ 0 \notin [b]. \quad (20)$$

We will present the interval values of the j-th characteristic of the LN construction variants $s_i, s_l \in S$ as intervals $A = [\xi_j^-(s_i); \xi_j^+(s_i)]$ and $B = [\xi_j^-(s_l); \xi_j^+(s_l)]$ through their centers and radii $A = [\hat{a}; \ \bar{a}]$ and $B = [\hat{b}; \ \bar{b}]$ where $\hat{a}$, $\hat{b}$, $\bar{a}$, $\bar{b}$ – centers and radii of intervals *A* & *B*:

$$\hat{a} = [a^- + a^+]/2, \ \bar{a} = [a^+ - a^-]/2,$$

$$\hat{b} = [b^- + b^+]/2, \ \bar{b} = [b^+ - b^-]/2. \quad (21)$$

Then, the generalized Hukuhara difference for the interval values of the characteristic $A = [\hat{a}; \ \bar{a}]$ and $B = [\hat{b}; \ \bar{b}]$ $A \overset{-}{_{gH}} B$ and the comparison index $\gamma_{A,B}$ can be determined by the relation [44]:

$$A \overset{-}{_{gH}} B = \begin{bmatrix} \min\{a^- - b^-; a^+ - b^+\}; \\ \max\{a^- - b^-; a^+ - b^+ \end{bmatrix} = \\ = (\hat{a} - \hat{b}; |\bar{a} - \bar{b}|); \quad (22)$$

$$\gamma_{A,B} = (\bar{a} - \bar{b})/(\hat{a} - \hat{b}). \quad (23)$$

The proposed use of utility functions (16) in optimization problems (14) changes the problems of minimizing local criteria $k_j(s) \to \min\limits_{s \in S}$ to problems of maximizing $\xi_j(s) \to \max\limits_{s \in S}$. Taking this into account, under the condition of a positive average gain $\hat{a} > \hat{b}$, the following situations of intersection of intervals are possible [44]: $a^- < b^-$, $a^-$and b^-, $a^+ < b^+$ and $a^+$and b^+.

Situation 1: $a^- < b^-$ – the ratio of losses in the worst case to the average gain is:

$$I_1(A,B) = (a^- - b^-)/(\hat{a} - \hat{b}) = 1 - \gamma_{A,B} < 0 . \quad (24)$$

Situation 2: $a^-$and b^- – there are no losses in the worst case:

$$I_2(A,B) = (a^- - b^-)/(\hat{a} - \hat{b}) = 1 - \gamma_{A,B} > 0 . \quad (25)$$

Situation 3: $a^+ < b^+$ – the ratio of losses to the average gain in the worst case:

$$I_3(A,B) = (a^+ - b^+)/(\hat{a} - \hat{b}) = 1 + \gamma_{A,B} < 0 . \quad (26)$$

Situation 4: $a^+$and b^+ – there are no losses in the worst case:

$$I_4(A,B) = (a^+ - b^+)/(\hat{a} - \hat{b}) = 1 + \gamma_{A,B} > 0 . \quad (27)$$

The values of indices $I(A,B)$ (24)–27 indicate the ratio of possible losses and gains when choosing $A \succ B$ based on the comparison results $\hat{a} > \hat{b}$.

The proposed algorithm allows comparing network construction options for interval-presented input data both according to each of the local criteria (7) – (10) and according to the general criterion of efficiency assessment (15). Its use will allow obtaining both optimistic and pessimistic values of network characteristics when solving problems of its adaptation to conditions caused by the consequences of emergency situations.

Experiment results

Let us consider an example of ranking a set of options when solving the problem of adapting the topological structure of LN at the reengineering stage in conditions of interval certainty of input data in the following formulation.

The specified characteristics of effective network adaptation options set $S^E = \{s_i\}$, $i = \overline{1,8}$, which are evaluated according to three local criteria: reported costs, million c.u. $[k_1(s', s)] \to \min\limits_{s}$ (9); efficiency (maximum delivery time), hours $[k_2(s', s)] \to \min\limits_{s}$ (8); time to adapt the supply network, days $[k_3(s', s)] \to \min\limits_{s}$. The interval values of the utility functions of local criteria $\xi_j(s_i)$, $\xi_j(s_i)$, $i = \overline{1,8}$, $j = \overline{1,3}$, obtained using formula (16), are given in Table 2. The ratio of preference between local criteria is given by the values of their weight coefficients: $\lambda_1 = 0,3$; $\lambda_2 = 0,2$; $\lambda_3 = 0,5$.

It is necessary to rank the set of effective network adaptation options $s_i \succ s_j \succ ... \succ s_k$ according to indicator (15) and determine the best $s^o \in S^E$ among them.

For the given interval values of the utility functions of local criteria, we calculate the values of their centers and radii $\hat{\xi}_j(s_i)$, $\bar{\xi}_j(s_i)$, $i = \overline{1,8}$, $j = \overline{1,3}$ (21) (Table 2).

Table 2 – **Values of utility functions of local criteria for network construction options**

s_i	$\xi_1^-(s)$	$\xi_1^+(s)$	$\hat{\xi}_1(s)$	$\bar{\xi}_1(s)$	$\xi_2^-(s)$	$\xi_2^+(s)$	$\hat{\xi}_2(s)$	$\bar{\xi}_2(s)$	$\xi_3^-(s)$	$\xi_3^+(s)$	$\hat{\xi}_3(s)$	$\bar{\xi}_3(s)$
s_1	0,865	0,908	0,887	0,022	0,722	0,794	0,758	0,036	0,452	0,475	0,464	0,012
s_2	0,522	0,538	0,530	0,008	0,836	0,878	0,857	0,021	0,479	0,493	0,486	0,007
s_3	0,837	0,896	0,866	0,029	0,614	0,626	0,620	0,006	0,771	0,786	0,779	0,008
s_4	0,503	0,513	0,508	0,005	0,578	0,618	0,598	0,020	0,852	0,937	0,895	0,043
s_5	0,629	0,679	0,654	0,025	0,651	0,677	0,664	0,013	0,687	0,714	0,701	0,014
s_6	0,761	0,784	0,772	0,011	0,712	0,783	0,748	0,036	0,541	0,573	0,557	0,016
s_7	0,464	0,487	0,476	0,012	0,652	0,698	0,675	0,023	0,563	0,574	0,569	0,006
s_8	0,557	0,613	0,585	0,028	0,625	0,656	0,641	0,016	0,711	0,747	0,729	0,018

To determine the total value of the options $[P(s)]$, we will use the additive component of the ratio (15). The obtained values of the intervals $[P(s)]$, their centers $[\hat{P}(s)]$, and radii $[\bar{P}(s)]$ (21) are given in Table 3. Let us determine for the estimates of options $[P(s_i)]$ and $[P(s_{i+1})]$, $i = \overline{1,7}$ situations of intersection of their intervals (24) – (27), calculate the values of the coefficient $\gamma_{i,i+1}$ (23) and indices $I_j(P_i, P_{i+1})$, $j = \overline{1,4}$ (24) – (27) (Table 3). Analysis of the results obtained for the situations of intersection of intervals, values of the coefficient $\gamma_{i,i+1}$ (23) and indices $I_j(P_i, P_{i+1})$ indicates the disorderliness of the set of options under consideration. In particular:

– when comparing options $s_2 \succ s_3$, situations 1 and 3 occur, for which $I_1(P_2, P_3) = \mathbf{0,982} > 0$ and $I_3(P_2, P_3) = 1,018 > 0$, which does not correspond to conditions (24) and (26), respectively;

– when comparing options $s_7 \succ s_8$, situations 1 and 3 occur, for which $I_1(P_2, P_3) = \mathbf{0,9}15 > 0$ and $I_3(P_7, P_8) = 1,085 > 0$, which does not correspond to conditions (24) and (26). The results of their ranking using the proposed algorithm based on comparison indices and the characteristics of the ordered set of options are given in Table 4. The values of all comparison indices for situations 2 and 4 that occurred, $I_j(P_i, P_{i+1}) > 0$, $i = \overline{1,7}$, $j = 2, 4$, correspond to the preference conditions $s_i \succ s_l$, $i = \overline{1,7}$, $l = \overline{2,8}$ (25), (27).

Table 3 – **Meanings of the total values of the options, their centers, radii, and the results of their comparison**

s_i	$P^-(s)$	$P^+(s)$	$\hat{P}(s)$	$\bar{P}(s)$	Situations	$\gamma_{i,i+1}$	I_1	I_2	I_3	I_4
s_1	0,630	0,669	0,650	0,020	2, 4	0,118	0,882	**0,882**	1,118	**1,118**
s_2	0,563	0,584	0,574	0,011	1, 3	0,018	**0,982**	0,982	**1,018**	1,018
s_3	0,759	0,787	0,773	0,014	2, 4	-0,234	1,234	**1,234**	0,766	**0,766**
s_4	0,693	0,746	0,720	0,027	2, 4	0,235	0,765	**0,765**	1,235	**1,235**
s_5	0,662	0,696	0,679	0,017	2, 4	-0,105	1,105	**1,105**	0,895	**0,895**
s_6	0,641	0,679	0,660	0,019	2, 4	0,082	0,918	**0,918**	1,082	**1,082**
s_7	0,551	0,573	0,562	0,011	1, 3	0,085	**0,915**	0,915	**1,085**	1,085
s_8	0,648	0,688	0,668	0,020	–	–	–	–	–	–

Table 4 – **Values of quality assessments of options and indices of their comparison on an ordered set**

s_i	$P^-(s)$	$P^+(s)$	$\hat{P}(s)$	$\bar{P}(s)$	Situations	$\gamma_{i,i+1}$	I_1	I_2	I_3	I_4	Ranking
s_3	0,759	0,787	0,773	0,014	2, 4	-0,234	1,234	**1,234**	0,766	**0,766**	1
s_4	0,693	0,746	0,720	0,027	2, 4	0,235	0,765	**0,765**	1,235	**1,235**	2
s_5	0,662	0,696	0,679	0,017	2, 4	-0,273	1,273	**1,273**	0,727	**0,727**	3
s_8	0,648	0,688	0,668	0,020	2, 4	0,125	0,875	**0,875**	1,125	**1,125**	4
s_6	0,641	0,679	0,660	0,019	2, 4	-0,048	1,048	**1,048**	0,952	**0,952**	5
s_1	0,63	0,669	0,650	0,020	2, 4	0,118	0,882	**0,882**	1,118	**1,118**	6
s_2	0,563	0,584	0,574	0,011	2, 4	-0,043	1,043	**1,043**	0,957	**0,957**	7
s_7	0,551	0,573	0,562	0,011	–	–	–	–	–	–	8

In this case, the specified ordering of the set of effective options for reengineering the topological structure of LN for the interval-specified values of their total value index $[P(s)]$ (15):

$$s_3 \succ s_4 \succ s_5 \succ s_8 \succ s_6 \succ s_1 \succ s_2 \succ s_7 \qquad (28)$$

will fully correspond to the ordering by the values of the interval centers $\hat{P}(s_i)$, $i = \overline{1,8}$ (21).

Considering this, the best option in the process of reengineering the topological structure of LN based on the interval-specified values of the indicators of the above costs (9), efficiency (8), and network adaptation time (10) is the option $s^0 = s_3$, that has sufficiently high values of local utility functions for all indicators.

Conclusions

Based on the results of the analysis of the problem of optimizing the topological structures of logistics networks, it has been established that: the vast majority of optimization tasks are multi-criteria and combinatorial, and their input data is determined on the basis of forecast estimates or mathematical modeling with some errors; existing mathematical models and methods for optimizing global transportation networks do not allow solving problems while taking into account their rapid adaptation to the negative effects of external influences. This has led to the relevance of scientific and practical tasks for the development of effective mathematical models and methods for solving multi-criteria problems of rapid adaptation of logistics networks in conditions of incomplete uncertainty of input data.

Based on the results of the study, a solution to the scientific and practical problem of improving the effectiveness of technologies for the rapid adaptation of networks to the negative effects of emergencies was proposed by developing a mathematical model for their multi-criteria optimization in conditions of interval certainty of input data. To achieve this goal, the following were developed formulations of problems of rapid adaptation and reengineering of network topological structures to the negative effects of emergency situations; formalization of indicators for evaluating options for adapting network topological structures to the negative effects of emergency situations; Mathematical models were developed for optimizing topological structures under conditions of incomplete uncertainty of input data based on indicators of induced costs, operational efficiency, and network adaptation time. For the practical use of the developed models, an algorithm for comparing network construction options based on local and generalized criteria for interval-based estimates has been proposed.

The developed problem formulations, mathematical models, and algorithm expand the methodological foundations for automating the processes of supporting multi-criteria project decisions in the design and adaptation of micro-logistics network topological structures. They allow obtaining effective solutions to the problems of the fastest possible restoration of supply using the means that have remained after the onset of an emergency and the subsequent reengineering of the network construction option.

The practical application of the results obtained will make it possible to reduce the time required to restore supplies in the event of damage to elements and infrastructure of logistics networks, and, through the use of technology for selecting subsets of effective options with interval-specified characteristics, to guarantee the quality of project decisions and provide more complete assessments of them.

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Надійшла (received) 11.07.2025
Прийнята до друку (accepted for publication) 17.09.2025

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Адаптація структур логістичних мереж в умовах надзвичайних ситуацій

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Анотація. Предметом дослідження в статті є процес адаптації топологічних структур мікрологістичних мереж в умовах негативного впливу зовнішнього середовища. **Мета роботи** – є підвищення ефективності технологій швидкої адаптації логістичних мереж (ЛМ) до негативних впливів надзвичайних ситуацій шляхом розробки математичної моделі їх багатокритеріальної оптимізації в умовах неповної невизначеності вхідних даних. У статті вирішуються такі **завдання:** аналіз сучасного стану проблеми оптимізації при адаптації топологічних структур мереж до негативних впливів надзвичайних ситуацій; розроблення постановок задач швидкої адаптації топологічних структур мереж до негативних впливів надзвичайних ситуацій; формалізація показників оцінки варіантів адаптації структур ЛМ до негативних впливів надзвичайних ситуацій; розроблення математичних моделей задач багатокритеріальної оптимізації топологічних структур в умовах неповної невизначеності вхідних даних; розроблення алгоритму порівняння варіантів побудови мереж для інтервально поданих вхідних даних. Використовуються такі **методи**: теорії систем, теорії корисності, комбінаторної оптимізації, дослідження операцій, інтервальної та нечіткої математики. **Результати.** Для досягнення мети було розроблено постановки задач швидкої адаптації і реінжинірингу топологічних структур мереж до негативних впливів надзвичайних ситуацій; виконано формалізацію показників оцінки варіантів адаптації топологічних структур мереж до негативних впливів надзвичайних ситуацій; розроблено математичні моделі задач оптимізації топологічних структур в умовах неповної невизначеності вхідних даних за показниками наведених витрат, оперативності й часу адаптації мережі. Запропоновано алгоритм порівняння варіантів побудови мереж за локальними і узагальненим критеріями для інтервально поданих оцінок. **Висновки.** За результатами дослідження запропоновано рішення науково-практичної задачі підвищення ефективності технологій швидкої адаптації мереж до негативних впливів надзвичайних ситуацій шляхом розробки математичної моделі їх багатокритеріальної оптимізації в умовах інтервальної визначеності вхідних даних. Отримані результати розширюють методологічні засади автоматизації процесів підтримки прийняття багатокритеріальних проєктних рішень при проєктуванні та адаптації топологічних структур мереж мікрологістики. Вони дозволяють отримувати ефективні рішення задач максимально швидкого відновлення постачання з використанням засобів, що збереглися після настання надзвичайної ситуації та подальшого реінжинірингу варіанту побудови мережі. Практичне використання отриманих результатів дозволить скорочувати час відновлення постачання при ушкодженні елементів та інфраструктури логістичних мереж, а за рахунок використання технології виділення підмножин ефективних варіантів з інтервально заданими характеристиками – гарантувати якість проєктних рішень та надавати їх більш повні оцінки.

Ключові слова: логістична мережа; топологічна структура; адаптація; математична модель; прийняття рішень; багатокритеріальна оптимізація; інтервальний аналіз; теорія корисності.