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Assessment of the Structural Stability of Transport and Logistics Systems Based on Graph Models and the Percolation Coefficient

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ABSTRACT

Global changes in the global economy and trade place new demands on transport and logistics systems (TLS). Increasing their resilience to disruptions and structural changes is becoming a critical task amid the growing share of logistics costs in Russia's GDP. Existing optimization methods often do not take into account the resilience of the network structure itself to destructive influences, which creates a gap in knowledge. **The purpose** of the study is to develop and test methodological tools for assessing and improving the structural stability of the TL. **The approach** integrates graph-theoretical modeling, multi-criteria optimization methods, and a new indicator, the percolation coefficient, which characterizes the network's ability to deliver goods to all destinations. The multi-criteria optimization problem of finding paths and flows is formalized. Sustainability was assessed through the coefficient of influence of structural changes on the effectiveness of solutions. A large-scale computational experiment was conducted with the generation of more than 1 million graph structures. A mathematical model of the radar has been developed based on a matrix of initial conditions, and an efficiency coefficient has been proposed for comparing alternative options. A close correlation has been established between network bandwidth, percolation coefficient, and solution efficiency. The barrier values of the coefficient of influence have been determined, which make it possible to classify the system as stable or unstable to a specific type of structural failure. The principles of building sustainable radar stations are formulated, the key of which is the availability of alternative routes with efficiency close to optimal. **The results** obtained lay the foundation for the creation of intelligent radar stations that are resistant to failures and load fluctuations.

Keywords: transport and logistics system; structural stability; graph theory; multicriteria optimization; percolation coefficient; network modeling

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ОРИГИНАЛЬНАЯ СТАТЬЯ

Оценка структурной устойчивости транспортно-логистических систем на основе графовых моделей и коэффициента просачиваемости

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АННОТАЦИЯ

Глобальные изменения в мировой экономике и торговле предъявляют новые требования к транспортно-логистическим системам (ТЛС). Повышение их устойчивости к сбоям и структурным изменениям становится критической задачей на фоне роста доли логистических издержек в ВВП России. Существующие методы оптимизации часто не учитывают устойчивость самой сетевой структуры к деструктивным воздействиям, что создает пробел в знаниях. **Цель работы** — создать и апробировать методологический инструментарий для оценки и усиления структурной устойчивости ТЛС.

В рамках предложенного подхода объединены: графо-теоретическое моделирование; методы многокритериальной оптимизации; новый показатель – *коэффициент просачиваемости*, отражающий способность сети обеспечивать доставку грузов во все пункты назначения. **В ходе исследования:** формализована многокритериальная оптимизационная задача, направленная на поиск оптимальных путей и потоков; разработана математическая модель ТЛС на базе матрицы начальных условий; введен коэффициент эффективности для сопоставления альтернативных вариантов решений. Проведена оценка устойчивости через коэффициент влияния структурных изменений на эффективность решений. Выполнен крупномасштабный вычислительный эксперимент, в рамках которого сгенерировано свыше 1 млн графовых структур. **Основные результаты:** выявлена тесная корреляция между пропускной способностью сети, коэффициентом просачиваемости и эффективностью принимаемых решений; определены барьерные значения коэффициента влияния, позволяющие классифицировать ТЛС как устойчивую или неустойчивую к конкретному типу структурного разрушения; сформулированы принципы построения устойчивых ТЛС, среди которых ключевым является наличие альтернативных путей с эффективностью, близкой к оптимальной. Полученные результаты формируют фундамент для разработки интеллектуальных транспортно-логистических систем, способных эффективно противостоять сбоям и колебаниям нагрузки.

Ключевые слова: транспортно-логистическая система; структурная устойчивость; теория графов; многокритериальная оптимизация; коэффициент просачиваемости; сетевое моделирование

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INTRODUCTION

The past decade has marked a new phase in global economic development, characterized by significant shifts in the international division of labor. These changes necessitate a fundamental review of development and modernization strategies for transport and logistics systems (TLS) at both global and regional levels, as the creation and modernization of TLS will be a key determinant of long-term regional economic development.

As market volumes expand, effectively solving increasingly complex logistics tasks — many of which are NP-hard problems [1] — becomes more critical. In practice, however, it is possible to formulate constrained problems that admit polynomial algorithms [2–4]. For each specific task, solution effectiveness is determined individually [5, 6]. Equally important is examining not only the effectiveness of solutions but also the system's structural ability to deliver optimal outcomes — shifting the question from "how to find the optimum" to "how to build a system where solutions are optimal."

Modern business requirements underscore the critical importance of supply chain sustainability [6]. Given frequent disruptions and their severe consequences, ensuring structural stability is paramount. Meanwhile, the integration of systems and technologies — a key trend in TLS evolution — gives rise to multi criteria decision making tasks underpinned by big data, amplifying the prevalence of NP-hard problems and demanding novel research methodologies [7].

In Russia, transport and logistics expenditures constitute approximately 20% of GDP, significantly exceeding the global average of about 11%, with potential annual savings of up to 180 billion USD if aligned with global benchmarks. Key development factors include warehouse class, the level of logistics process optimization, and spatial uniformity of logistics centers.

This paper approaches TLS in an infrastructural sense, as a set of entities providing transportation, storage, and distribution of goods. The work aligns with research on managing structural dynamics of complex systems [7–9] and adapts methodological approaches originally developed for technical systems [10, 11] to analyze socio economic and organizational technical structures in TLS.

The primary objective is to develop a comprehensive toolkit for assessing the structural sustainability of TLS, addressing the following tasks: developing a graph theoretic model; formulating and solving a multi criteria optimization problem; determining structural failure processes; and calculating a quantitative stability coefficient. Stability analysis under network growth (e.g., expansion or scaling) falls outside the scope of this study and is reserved for future research [12].

MATHEMATICAL DESCRIPTION OF THE TRANSPORT AND LOGISTICS SYSTEM

We propose a graph theoretic approach for modeling transport and logistics systems. In this framework, any such system can be represented as a network comprising nodes (vertices) and a set of pairwise connections (edges) between them. Practically, nodes may correspond to physical or functional entities such as transfer hubs, stations, warehouses, or key reference points within the logistics network. Since the system consists of a set of logistic nodes and connections between them, it is natural to describe it with a graph $G(v,e)$, where the vertice $\{v\}$ are the nodes of the network, and the edges $\{e\}$ are the connections (channels) between them. The main range of tasks is reduced to searching for certain structures on the graph: flows, paths, routes, cycles, etc.

Considered a graph $G=(V,E)$ in which there are two types of vertices: $\{v\in V\}$ and $\{e\in E\}$, where

$\{v^1\in V^1\}$ и $\{v^2\in V^2\}, V^1\cap V^2=\varnothing, V^1\cup V^2=V$.

The vertices *of the first type* $\{v^1\}$ correspond to important nodes in solving typical problems (for example, the source/drain or the start/end point). They may not be key to a particular task, but they have the potential to become one. The remaining vertices $\{v^2\}$ are vertices of *the second type*. The vertex type is invariant with respect to particular problems and can change only for systemic and structural reasons.

In the graph $G=(V,E)$ the edges model the cargo transfer channels. Two vertices v_i^1 and v_i^2 can be connected by several multiple edges $\{e_{12}^{(1)},e_{12}^{(2)},\ldots\}$. The most important characteristics of edges are vector weight and throughput, which can be deterministic or non-deterministic. The weight reflects the resources for communication (cost, time, etc.). Bandwidth sets channel limits (number of shipments, total weight of cargo, etc.).

In mathematical terms, a product is formalized as an *element of a task*. A set of M elements of the problem is considered. For this set of problem elements, we define a collection of *P* features, which correspond to the weight coefficients assigned to the graph edges. The initial conditions of the systemre represented by a four dimensional matrix *I*, whose elements are denoted as I_{ijmp}, where

$$i=\overline{1,N}\ ,\ j=\overline{1,N}\ ,\ m=\overline{1,M}\ ,\ p=\overline{1,(P+1)}.$$

Indexes *i* and *j* define the edges, *m* — is the element of the problem, and p is the feature (the bandwidth of the edge for the element is added to the initial *P* features). The flow of task elements is denoted by *f*. The optimization criterion is written as $Z(I,f)$, and the task is represented as $Z(I,f)\to opt$.

For each flow *f* there is a solution $s(I,f)$, which is a graph structure (usually a path in a graph). If a different path is searched for each element, the task degenerates into *M* separate subtasks. When comparing different solutions, the value of the objective function *Z*(s) is evaluated. The optimal solution s_{opt} corresponds to the maximum achievable value of the criterion, denoted as $Z_{opt}=Z(s_{opt})$. *The efficiency coefficient* k_{eff} of any solutions s is defined as the ratio of its objective function value to that of the optimal solution:

$$k_{eff}=\frac{Z(\mathrm{s})}{Z_{opt}}.$$

The tasks in the system are divided into four groups:

1. The task of finding the (optimal) path between two key points.
2. The task of finding the optimal flow through the network, taking into account the bandwidth of the edges.
3. The combined task of taking into account the weights of the edges and their throughput.
4. Other tasks that do not require network modeling.

The first three groups are called *basic tasks*. The most common task is the third group, therefore, in the future, the *basic task* is understood as it is.

The weight and throughput of the edges are vector-based and may be non-deterministic. Structural disruptions can change the solutions to basic problems. It is assumed that *the solution existing on the original graph structure is optimal* (the reference). Comparison of other solutions is carried out with him.

PERCOLATION THEORY

Percolation Theory[1] has not previously been used to describe transport and logistics problems [13]. This paper suggests a new approach that may be promising for global transportation planning.

One or two central vertices are highlighted on the graph as *the source* (for example, large network nodes) [14]. *The peripheral* vertices corresponding to the recipients of the goods are considered drains. This representation is applicable both for the tasks of finding the least expensive path and for optimizing flows.

The flow path $P(V)$ of the graph $G=(V,E)$ is defined as the shortest directed path from the central vertex to a given peripheral vertex $v\in V$. For each vertex v, the set of all such flow paths is finite and is denoted by V_P. Correspondingly, *the stream chain* $S(V)$ is defined as the shortest undirected path from the central vertex to a peripheral vertex v. The finite set of all stream chains for a given vertex is denoted by $V_S(v)$. *The Percolation coefficient* is defined as

$$k_p=\frac{|V_P|}{|V_S|}.$$

If $k_p>0$ there is at least one streaming path, i.e. delivery is possible to one destination. At $k_p=1$ the flows reach all drains. The coefficient can vary over time due to structural changes (congestion, disasters) and is defined for different classes of graphs. This approach allows us to describe the problem using a graph model, which can be used to solve various classes of

[1] Work on network connectivity metrics, developing ideas close to the theory of infiltration.

problems, including the multi-criteria maximum flow problem, where the percolation coefficient becomes the key criterion.

THE UTILITY FUNCTION OF THE SOLUTION

Each system is designed to solve specific tasks; the processes on it influence decisions. The most important process is changing the weights of the edges, since structural changes are a special case of it.

Two types of tasks are considered:

1. Minimizing resource costs: $f(x) \to min$, where x is a vector set of features (time, cost, etc., possibly non-deterministic).

2. Load optimization: $g(y) \to min$, where y is a vector of flows and throughput. The minimum corresponds to a uniform distribution.

In practice, simultaneous solutions are more often required, which leads to a third type of problem. *The utility function of the solution* is introduced, which is a combination of optimization functions with weighting coefficients:

$$P(x, y) \to max.$$

The usefulness of the optimal solution is:

$$P_{opt} = \max_{\forall x, y} \left(P(x, y) \right).$$

The utility coefficient of the solution found is

$$k_u = \frac{P}{P_{opt}}.$$

The dynamics of all key system processes are modeled via changes in vertex and edge parameters, including their weights and throughput. Each such change can be decomposed into a finite sequence of elementary transformations applied to the graph *G*.

Resistance to structural damage is being investigated. Any change in the structure entails a change in the matrix *I* (the weights of the edges of the complete graph). The correspondence of elementary structural changes to the modifications of matrix I is shown in *Table*.

Structural destruction is a set of elementary actions of removing vertices and edges of a graph. Deleting a vertex entails deleting incident edges.

A change in the structure leads to a change in the set of solutions $\{s\}$ and the optimal solution s_{opt} relative to the criterion $Z(s)$. If a structural modification causes the optimal solution to shift from s_1 to s_2, the *coefficient of structural influence* k_{inf} is defined as the ratio of their corresponding objective function values:

$$k_{inf} = \frac{Z(s_2)}{Z(s_1)}.$$

For processes representing structural degradation or removal (e.g., vertex/edge deletion), we have $Z(s_2) \le Z(s_1)$, which implies $k_{inf} \in [0,1]$. The magnitude of k_{inf} reflects the severity of the disruption: if it remains within a predefined acceptable threshold, the system can be considered structurally resilient to the given impact.

Table

Correspondence of Structural Changes to Changes in the Adjacency Matrix

No.	Structural Change	Corresponding Change in Matrix I
1	Removal of vertex v_i	Modification of all values I_{ijmp} to 0 or ∞ depending on the semantic meaning of the corresponding value *p*
2	Addition of vertex v_i	Modification of all values I_{ijmp} (from 0 or ∞ depending on the semantic meaning *p*) to actual values
3	Removal of edge e_{ij}	Modification of values I_{ijmp} to 0 or ∞ depending on the semantic meaning of the corresponding value *p*
4	Addition of edge e_{ij}	Modification of all values I_{ijmp} (from 0 or ∞ depending on the semantic meaning *p*) to actual values
5	Change in edge e_{ij} throughput	Modification of values I_{ijmp} (to corresponding updated values)
6	Change in vector weight of edge e_{ij}	Modification of values I_{ijmp} (to corresponding updated values)

Source: compiled by the authors.

Calculating the efficiency coefficient k_{eff} with a modified structure allows us to judge the stability of a particular solution and the system as a whole. The method also allows you to study the dependence of efficiency on the flows of task elements, estimating the allowable load.

The approach has the potential to solve the inverse problem of building systems that are resilient to changes in the usefulness of solutions during structural changes or load scaling. The paper examines the structural stability of the model to external influences (for example, failures of nodes or channels, which corresponds to the removal of vertices or edges). This will make it possible to assess the viability of existing systems and formulate requirements for creating new ones that are optimally sustainable.

A NUMERICAL EXAMPLE OF CALCULATING THE EFFICIENCY COEFFICIENT OF SOLUTIONS

A primary challenge in formulating the optimization problem lies in determining appropriate weighting coefficients for each resource. For illustration, consider two key resources: time T and transportation cost C. In this case, the optimization function can be expressed as $f(x) = TC \rightarrow min$. Within the graph model, the total time and cost of delivery are computed as the sum of the corresponding values along the edges of the selected path. Accordingly, the utility function takes the form

$$(T, C) = \frac{C_0}{TC}, \text{where } C_0 = const.$$

To demonstrate, we analyze a system with predefined edge weights representing cost and time. The objective is to determine the optimal path from vertex A to vertex B.

The path ADB s identified as optimal. The proposed method enables comparison of alternative solutions against this optimum via the efficiency coefficient k_{eff}. For instance, the path ACB exhibits a 30% reduction in efficiency relative to the optimal solution, while the path ADCB incurs efficiency losses exceeding 50%. *Fig. 1* shows the conditions of the problem and the calculation of the efficiency coefficient for different solutions.

Next, the combined task of optimizing the flow, taking into account the bandwidth, is considered. There are two goods; the capacity of the edges is set in the format (c_1, c_2). It is necessary to deliver a batch (t_1, t_2) from A and B. The bandwidth of the path is $c = (c_1, c_2)$. The optimization function for the flow is defined as:

$$g(c_i) = \begin{cases} 1, & c_i \geq t_i; \\ [t_i / c_i] + 1, & c_i < t_i, \end{cases}$$

where $g(c_i)$ is the component of the vector $g(c)$ corresponding to the i-th product.

The utility function for a correct solution (for incorrect ones, $P = 0$) has the form:

$$P(T, C, c) = \frac{840}{\sum_{i=1}^{2} (TC)_i \cdot g(c_i)},$$

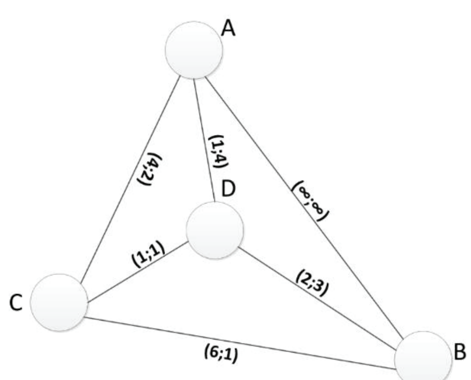
where $(TC)_i$ may be different for each product if they go their separate ways. *Fig. 2* shows the conditions of the problem and calculations of the utility function for different solutions.

The optimal solution is to send product 1 via ACB, and product 2 via ADB. Then:

$$P_{opt} = \frac{840}{3*7*2 + 10*3*1} = 11.7.$$

Both items cannot be shipped via ACB ($P = 0$). When sending both over ADB:

$$P = 10,\ k_{eff} = \frac{10}{11.7} = 0.86.$$



Path	C, cost	T, time	$P(x) = \frac{840}{TC}$	k_{eff}
AB	∞	∞	0	—
ADB	3	7	40	1
ACB	10	3	28	0.7
ADCB	8	6	17.5	0.4375

Fig. 1. **The Task of Finding the Optimal path From Vertex A to Vertex B**

Source: Author's calculations.

CONSTRUCTION OF TRANSPORT AND LOGISTICS SYSTEMS WITH SPECIFIED PARAMETERS OF STRUCTURAL STABILITY

The concept of structural stability makes sense only with respect to a specific task $Z(I,f)\rightarrow opt$ and a given barrier value of k_{bar} which allows us to assess the impact of changes on the solution.

The opposite problem is relevant — the construction of systems resistant to structural damage. With a given k_{bar} for each flow f the stability of system I can be estimated. Flow f determines the departure/destination nodes and cargo volumes. The function $Z(I,f)\rightarrow min$ is non-decreasing with increasing traffic volume. If the system is stable for flow f, then it is stable for flow f_0 with smaller or equal volumes.

In practice, it is important to determine the maximum flows of goods that the system can handle. To assert the stability of system I at given maximum volumes and k_{bar} it is necessary to investigate solutions $Z(I,f)\rightarrow min$ and estimate k_{inf} for all possible — routes.

A large-scale computer experiment was conducted involving the random generation of over 1 million instances of the initial condition matrix I_{ijmp} for graphs comprising 50 to 100 vertices. The results indicate that a significant proportion of the generated systems demonstrate resilience to elementary structural damage, defined as the removal of individual edges or vertices. Specifically, with a stability threshold set at $k_{bar}=0.81$, more than 88% of the systems were classified as resistant.

The highest degree of stability was observed in systems possessing one or more vertex disjoint alternative solutions, where the objective function value $Z(s)$ of each such solution deviated from the optimal value by no more than 5.1%. Remarkably, among systems featuring two or more edge disjoint solutions, the proportion of stable configurations reached 99.94%.

INVESTIGATION OF THE CONGESTION FORMATION PROCESS

The introduced definitions make it possible to investigate the relationship between the characteristics of the system and structural changes with the coefficient of infiltration k_p. This makes it possible to assess the impact of congestion (which changes the capacity of edges) on the effectiveness of solutions.

For the experiment, a model of a connected network of 100 nodes was generated, described by a complete graph (the bandwidth of some edges is 0, which corresponds to a lack of connectivity). Congestion can lead to zero throughput at a discrete point in time, which is equivalent to removing an edge.

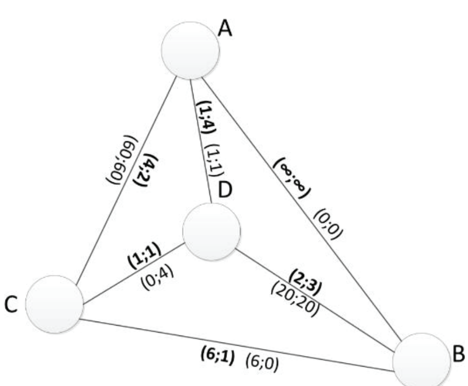
Next, random iterative changes in edge weights are modeled in the direction of increasing (decreasing throughput), corresponding to the formation of congestion. The model is anisotropic: the process of weight reduction is reversed without loss of accuracy, which makes it possible to describe both the formation and “resolution” of congestion. For the same limit values, the difference in averages is statistically insignificant.

Structure I covers 9900 typical delivery tasks with different departure and destination nodes. For each task, $Z_{opt}=Z(s_{opt})$ and k_p are defined.

At each iteration, Z (s) for the new optimal solution and k_p are calculated.

The result of the simulation is the value of

$$k_{eff}=\frac{Z(s)}{Z_{opt}},$$



Path	C, cost	T, time	c_1	c_2	$\frac{840}{TCg(c_1)}$	$\frac{840}{TCg(c_2)}$	P
AB	∞	∞	0	0	0	0	0
ADB	3	7	1	1	20	20	10
ACB	10	3	6	0	28	0	0
ADCB	8	6	0	0	0	0	0

Fig. 2. **The Combined Task of Finding the Optimal Path from Vertex A to Vertex B**

Source: Author’s calculations.

veraged over all tasks. A correlation was found between the average throughput of the edges (normalized *n*) and the values of k_p (*Fig. 3*).

The dependence of k_p on *n* is well approximated by a third-degree polynomial (correlation coefficient 0.976). With this level of correlation, it is possible to study the dependence of k_{eff} and k_p without taking into account the detailed throughput of individual edges, which simplifies calculations (*Fig. 4*).

At first, the change in k_p has little effect on k_{eff} then there is a sharp exit to a plateau (k_p range from 0.4 to 0.65), where k_{eff} stabilizes, after which it increases again.

The experiment was repeated for different configurations of parameters and graphs. The graph type is preserved, the plateau is always the same. The values of k_{eff} on the plateau lie within the boundaries of [0.615; 0.72]. This allows us to draw a parallel with

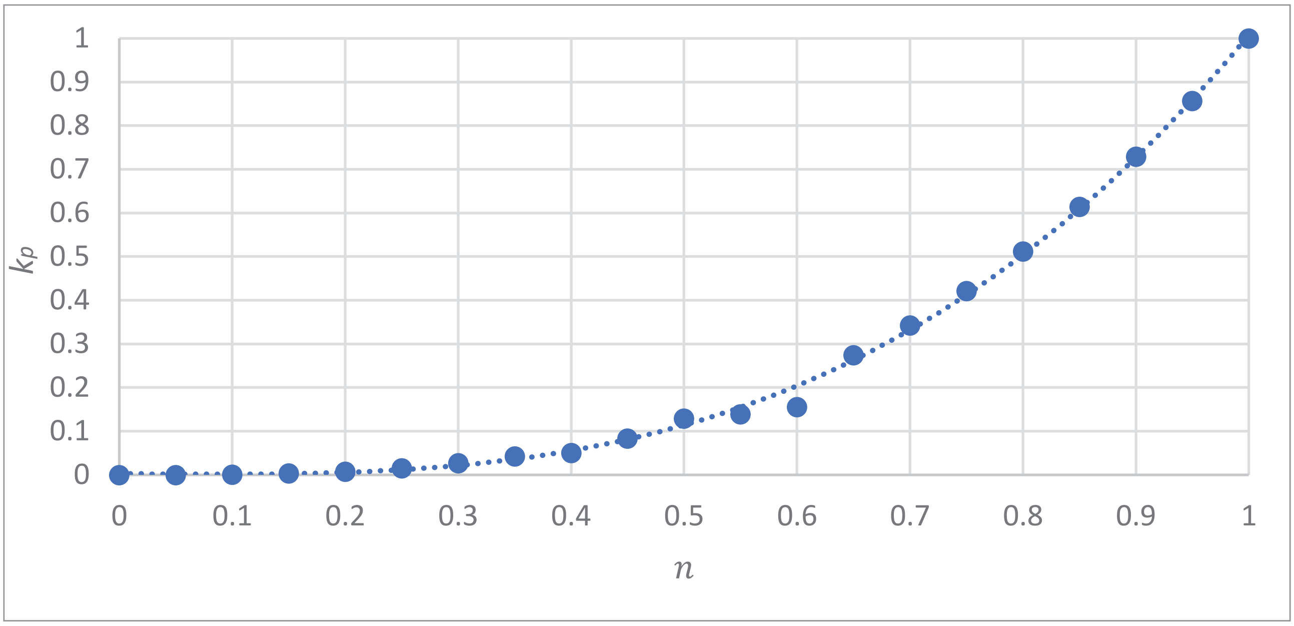


Fig. 3. **Dependence of k_p on the Normalized Average Throughput of Edges *n***
Source: Author's calculations.

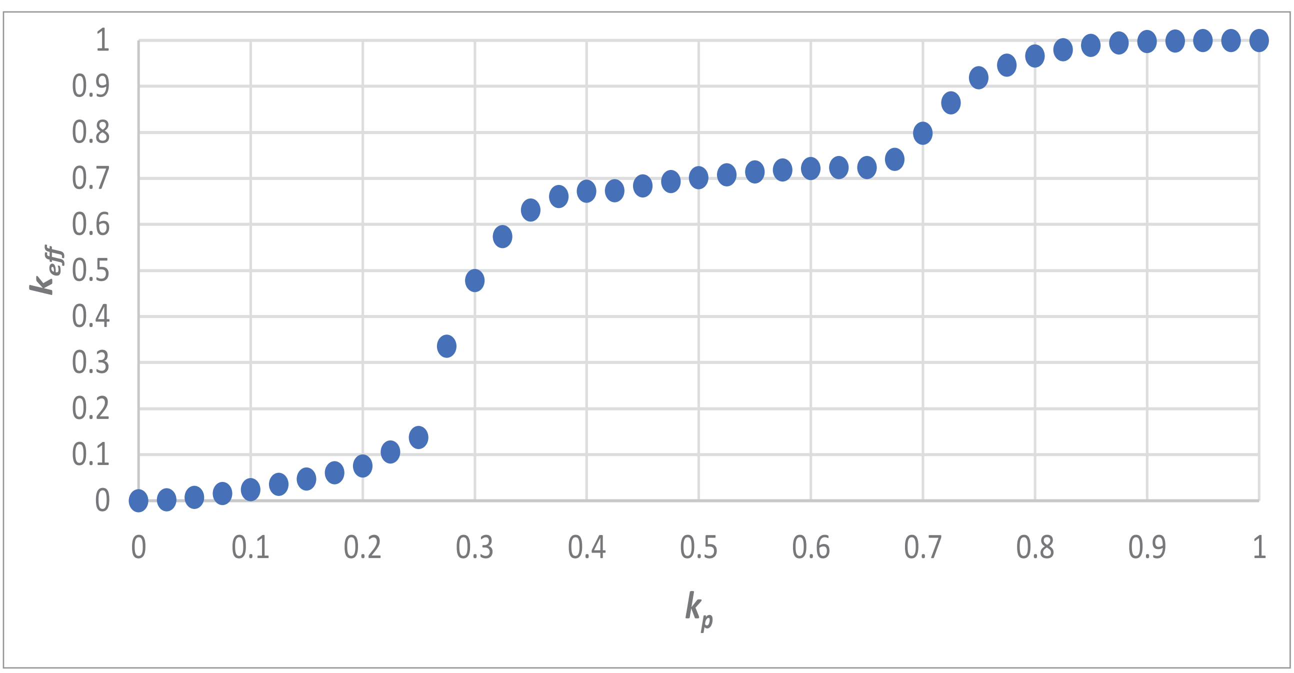


Fig. 4. **Dependence of k_{eff} on k_p**
Source: Author's calculations.

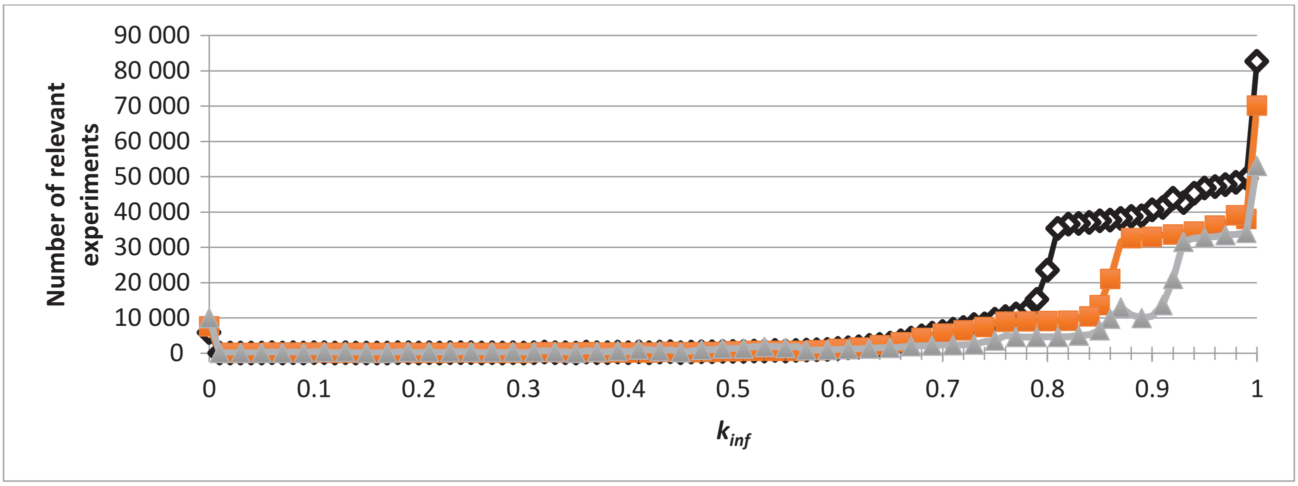


Fig. 5. **Number of Experiments and k_{inf}.**

Source: Author's calculations.

Note: Upper graph – removal of one element; Middle graph – removal of two elements; Lower graph – removal of three elements.

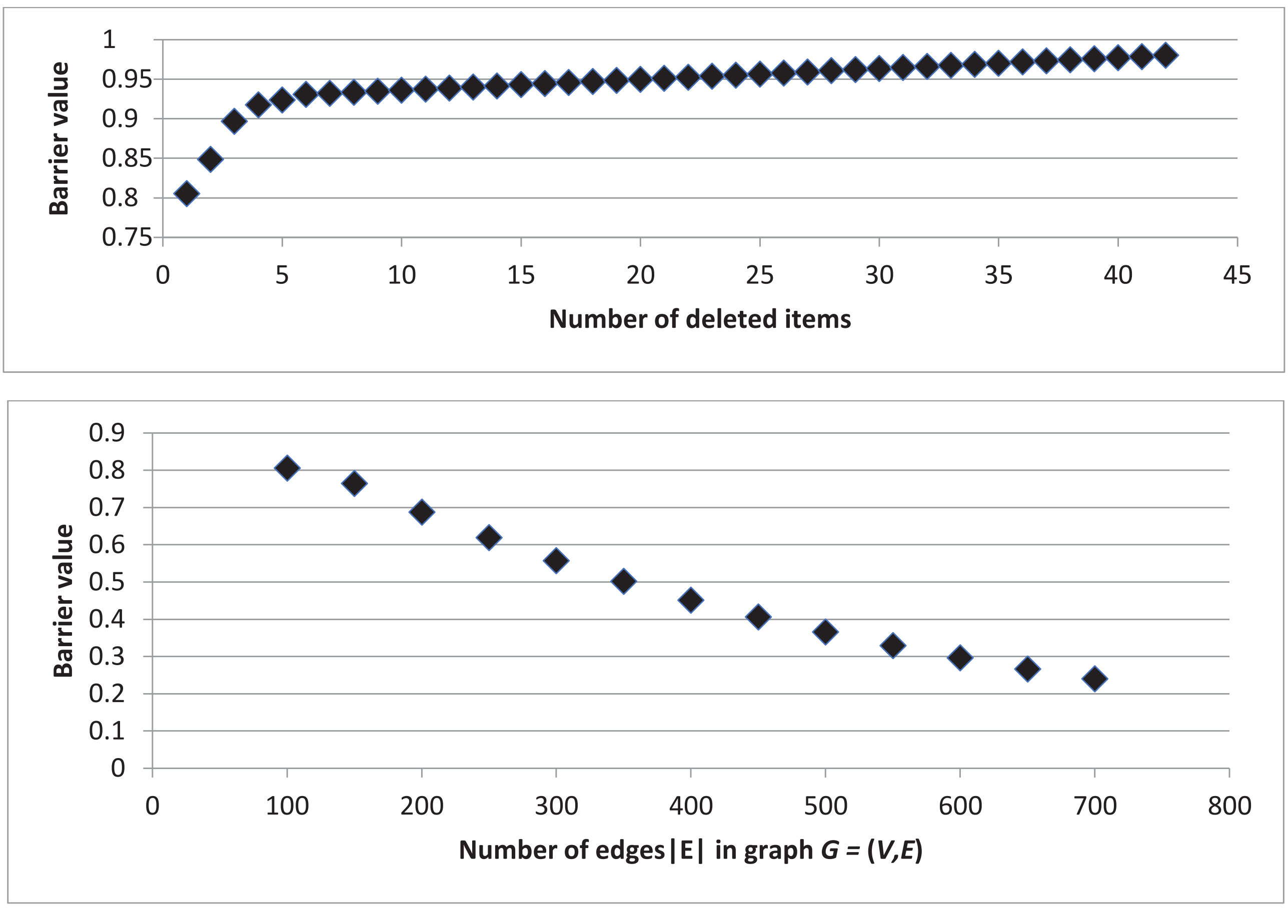


Fig. 6. **Number of Experiments and values k_{inf}**

Source: Author's calculations.

Note: The upper graph is the dependence of the barrier value on the number of elements to be removed. The lower graph is the dependence of the barrier value on $|E|$.

the barrier values of the coefficient of resistance to structural damage, since changes in k_p are associated with changes in the throughput of the edges, and structural destruction is their degenerate case [15].

Thus, the model allows not only to assess the impact of changes in throughput on problem solving, but also to make a priori forecasts of efficiency changes with characteristic changes in throughput.

COMPUTER MODEL CALCULATIONS

To determine the barrier value of k_{bar} a computer experiment was conducted to model transport and logistics systems and structural failure processes. 1,050,000 structures were generated with graphs $G(V, E)$ of size $|V| = 100$, matrices of initial conditions I and optimization criteria $Z(s)$.

The structural resistance to the removal of one element (vertex or edge) was studied using the coefficient of influence k_{inf}. The dependence of the number of systems on the value of k_{inf} is shown in *Fig. 5*. Jumps at $k_{inf} = 0$ and $k_{inf} = 1$ correspond to a complete loss of solvability or lack of influence on the optimal solution.

The appropriate range of acceptable values of k_{inf} for stability is considered to be [0.81; 1]. In 83.25% of the experiments 874 114 $k_{inf} \geq 0.81$. The point 0.81 corresponds to a loss of efficiency of up to 19%. In the range [0.81; 0.83] there is a sharp jump in the derivative, which divides all systems into two groups. Thus, $k_{inf} = 0.81$ is recommended as a barrier value for destruction of the "removal of one element" type. Systems with $k_{inf} < 0.81$ are considered unstable.

Additionally, resistance to removal of two and three elements was investigated. The barrier values were 0.86 and 0.90, respectively. The dependence of the barrier value on the number of elements to be deleted and the size of the graph is shown in *Fig. 6*: the barrier value increases with the number of elements to be deleted and decreases with the size of the graph.

The coefficients k_{inf} and k_{bar} provide a numerical measure of structural stability, allow us to analyze specific systems and solve the inverse problem of finding the optimal structure resistant to specified damage.

CONCLUSION

This paper develops a comprehensive methodological framework for studying transport and logistics systems (TLS), integrating principles from optimal control theory, multi criteria optimization, and graph theory. We introduce key formal concepts, including structural graph destruction, the combined transport logistics problem, and two central quantitative metrics: the solution efficiency coefficient k_{eff} and the structural influence coefficient k_{inf}.

A series of computer simulations modeling various structural damage scenarios were conducted. The experimental results enabled us to characterize the distribution of k_{inf} for elementary failure processes and to establish a threshold for acceptable performance degradation. Specifically, a system is considered to remain in a stable state if $k_{inf} \geq 0.81$ for the removal of a single network element (vertex or edge).

The theoretical significance of this work lies in its potential application to the design and analysis of resilient transport and logistics networks. The practical value stems from the development of accessible tools for assessing the structural sustainability of existing systems and for identifying critical vulnerabilities.

The results lay the foundation for further research on the dependence of stability on the characteristics of systems and the maximum volume of commodity flows. The proposed approach allows us to solve the inverse problem of building systems with a given structural stability, as well as to investigate the effectiveness of solutions depending on the load.

The prospect is to test the model on real data from logistics companies, as well as expand it to a multiparametric formulation with fuzzy weights and develop appropriate algorithms. The model is considered as an element of future intelligent transport and logistics systems in demand in the global transportation market.

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