Від вирішення проблеми формування раціональної структури територіальних транспортних систем і їх ефективного розвитку в значній мірі залежить розвиток промислових зон, районів і цілих регіонів. Особливості функціонування територіальних транспортних систем тісно пов'язані з їх структурою, яка характеризується деякою комбінацією парних показників близькості. Функціонування таких систем тісно пов'язане зі своїми структурою. Структура будь-якої транспортної системи є багаторівневою. Для уточнення числа структурних рівнів системи та складових їх елементів розроблені критерії й алгоритми, що дозволяють визначати взаємне розташування зазначених множин на площині з урахуванням можливого їхнього перекриття. Розроблений узагальнений показник близькості декількох множин, що не перекриваються, заснований на обліку парних показників близькості окремих множин і рівний їхньому середньому квадратичному значенню. Процедура структурного аналізу транспортної системи пов'язана з необхідністю попереднього визначення її структурного індексу за результатами розрахунків значень парних показників близькості. Розроблено метод встановлення числа структурних рівнів міжрегіональної транспортної системи заснований на попередньому визначенні структурного індексу системи з наступним прийняттям рішень по об'єднанню множин, що перекриваються, при їхній наявності. Рішення практичних завдань, пов'язаних з уточненням структури, складу й режимів функціонування транспортних систем слід виконувати на основі попередньо встановлюваного структурного індексу. Результати дослідження дозволяють структурувати транспортні системи з виділенням окремих рівнів, диференціювати витрати на їх розвиток та експлуатацію з метою оптимізації їх властивостей

Ключові слова: транспортна система, структурний аналіз, структурний індекс, структурний рівень, алгоритм структурування

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STRUCTURAL ANALYSIS OF TERRITORIAL TRANSPORT SYSTEMS BASED ON CLASSIFICATION METHODS

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1. Introduction

Production activity of industrial enterprises of every description relates to the necessity of cargo transportation in the delivery of raw materials, semi-finished products, finished goods. Transport systems and all necessary territorial infrastructure are created to meet transportation needs. The formation and development of such systems are closely related to the features and volumes of regional production, availability of stable transport links between enterprises and the prospects for further development of industrial zones and territories [1].

The transport system is a network with infrastructure which, in turn, has a set of elements for each type of transport that facilitate and ensure passage of material flows. The present study relates the development of a method of optimizing the transport network structure with the aim of classifying its levels according to the criterion of load level and utilization and subsequent distribution of capital and current expenditures for development and operation of infrastructure.

The problems of forming the rational structure of the transport system and improving its efficiency in current conditions are quite relevant. The range of ways to solve these problems is wide enough: from the application of intelligent control systems [2–4] to the development of new models and methods of organizing work and operation of vehicles [5, 6]. This is brought about by the generally high cost of construction of transport communications, infrastructure, repair, and maintenance. From an operational point of view, the territorial transport system is a set of transport routes, hubs, warehouses, distribution centers and other infrastructure elements. This promotes effective motion of transport and material flows in the process of enterprise production and economic activities.

It should be noted that despite the existence of known modeling methods, there is no a basic method of structuring transport systems simple and accessible enough to understand it and use in practice and which would make it possible to lay (as early as at the initial stage of designing) such elements that will improve efficiency of transport systems and manifest itself in operation. This is directly or indirectly confirmed in the studies analyzed in what follows. Therefore, analysis of the transport system structure both at the design stage and during operation is provided in the context of improving transport system efficiency as one of the most important factors.

2. Literature review and problem statement

Adoption of sound design solutions related to the formation of a transport network, reconstruction of existing sections, enhancement of existing road flyovers and other elements of infrastructure should be consistent with the general concept of balanced regional development [7]. It should be borne in mind that production links between individual entities are formed, as a rule, at the local level where long-term transport links arise.

There are several approaches to analysis and assessment of transport system efficiency [8, 9]. The statement of problems modeled by stationary Kolmogorov-Feller equations with a nonlinear drift coefficient is proposed in [10]. A mathematical analysis of the model is presented. The proposed method is based on the use of the Fourier transform to obtain an analytical solution to the problems in question. The problems discussed in [11] are related to the assessment of the functioning of complex technical systems, in particular, transport systems. It was assumed that the assessment of their functioning depends on the degree of meeting the chosen criteria. Therefore, it is important to define a set of criteria including their type, number, and value. Thus, choice and determination of importance of significant variables over time, measured and independent characteristics determine the degree of fulfillment of the criteria that serve as a basis for evaluating the functioning of such systems.

The DEA model based on the fuzzy theory and used for evaluating the efficiency of transport systems and services taking into account uncertainty of the data and assessment results was obtained in [12]. In particular, attention is given to "delay time" which is an important input data that is usually impossible to measure and is still considered to be indefinite. Study [13] addresses the problems associated with the quality assurance of transport systems. A concept of system operation quality was defined. Based on this concept, a schematic model of assessment was developed and a random process to be used for assessment was described. A model of assessment of system operation efficiency for analyzed technical objects was developed using semi-Markov theory. However, the issue of determining an index that can be used to assess and compare various different transport systems remained unsolved.

Territorial transport systems operating within established boundaries are considered in [14] as a set of sources and consumers of traffic flows interacting on the basis of a single transport network for satisfaction of existing freight needs. At the same time, it is important that the system structure in general is rational, consistent with existing needs and prospects of balanced regional development. Studies [15, 16] also point out that creation and maintenance of transport systems, their reconstruction and technical re-equipment require involvement of significant financial resources with a preliminary assessment of economic efficiency. However, relationship between efficiency of the system and its structure remains unclear.

Despite the wide spectrum of issues that have already been resolved, there are still many issues concerning improvement of structural analysis and raising efficiency of transport systems. It should be noted that such approaches to analysis of transport systems do not answer the question of determining the number of structural levels of complex systems and the generalized criterion characterizing their structure.

Time and cost are the main criteria for evaluating the efficiency of transport systems. It is obvious that the transport system structure and its individual elements (length of roads, their load level, time of movement, infrastructure, operating costs, etc.) are related to these criteria. This is directly and indirectly confirmed in [7–13].

In general, it can be said that efficiency of operation of the territorial transport system relates to the features of interaction between individual subsystems, structural elements and characteristics of logistical operations, processes and technologies used in practice.

Current methods of analysis and optimization of parameters of the process of the territorial transport system functioning are aimed at the improvement of existing and development of new technologies for the interaction of structural elements [17]. The technologies, operations and processes used must be adapted to the existing structure of the system [18]. However, the technical literature available does not present systematic analysis of various structures and properties of the transport systems built on their basis. Classification of structural elements is essentially formal and does not enable, in some cases, an objective assessment of their role and production potential across the entire transport system.

At present, the issues of structural analysis and synthesis of territorial transport systems have not been fully worked out which creates difficulties both in assessing the functionality of existing systems and designing new ones.

3. The aim and objectives of the study

The study objective is to develop an algorithm of analysis of regional transport system structure using the method of decomposition and system integration on the basis of structural indexes, which will enable solving specific problems to decide on their structure, composition and modes of operation.

To achieve this objective, the following tasks were set:

– to develop a method of decomposition of a transport system for singling out individual levels and work out criteria characterizing them;

– to develop a method for determining the structural index using system integration;

– to develop a method for establishing the number of structural levels of the interregional transport system.

4. Decomposition of the transport system to single out individual levels

Analysis of structure and decomposition of territorial transport systems is performed to determine the composition, properties, nature, and features of interaction of individual elements in the functioning process. This makes it possible to assess the suitability of such systems to solve problems determined by their purpose.

The list of typical problems arising in the formation and organization of functioning of territorial transport systems [19–21] are given in Table 1.

Solving the listed problems at individual stages of design, operation, reconstruction, and development of systems necessitates the periodic assessment of their current state and substantiation of expediency of making specific management decisions.

A structure of the transport system can generally consist of three interdependent levels differing in their composition and functions performed [22]. However, the number of structural levels may be less than three, and known methods of structural analysis do not make it possible to unambiguously determine their number and composition. This creates difficulties in solving practical problems including the choice of optimal operation modes.

Table 1

Typical problems arising in development and organization of functioning of territorial transport systems

List of problems of formation of structure and organization of functioning of transport systems	Corresponding stage of design or functioning related to solution of the set task
The task of analyzing and determining suitability of the structure of the existing transport system to the needs of the areas associated with freight traffic	Solved at the stage of nominal operation of the system to assess the possibility and feasibility of optimizing the modes of its functioning at different levels
The problem of synthesis and optimization of structure of multilevel transport systems taking into account the planned needs for organization of freight traffic	Solved at the stage of designing and forming structure of the transport network in development of new territories and areas
Decision-making problems related to gradual (evolutionary) development of territorial transport systems and bringing their structure and state into line with the changing needs of local, regional, and interregional freight traffic	Solved at the stage of reconstruction, modernization, improvement, and development of existing transport systems

Let us consider, as an example, a fragment of territorial transport system shown in Fig. 1.

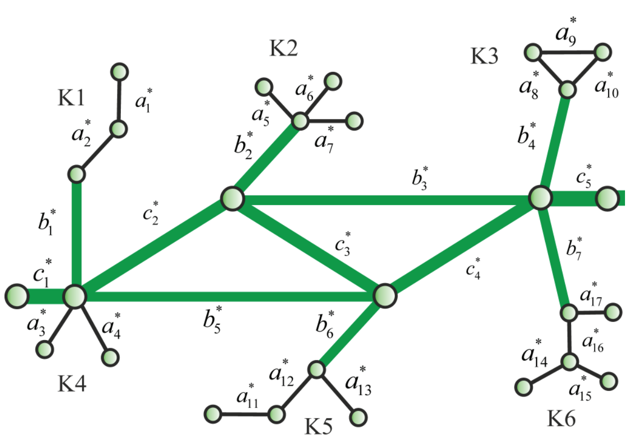


Fig. 1. A fragment of the territorial transport system

It consists of six interacting clusters K1, K2,..., K6, each containing transport routes of different lengths.

An aggregate of routes of such sections forms the composition of the local system level. For the fragment shown in Fig. 1, linear elements of the local level are denoted by a_i^* (i=1, 2,... 17) and form the set A^*.

In turn, the roads connecting nodes of individual clusters with the formation of a single transport network at the regional level are also linear elements of the system. These areas in Fig. 1 are denoted by b_i^* (i=1, 2,... 7) and their set determines the set B^*.

The system also contains elements that ensure passage of transit freight flows which are denoted by c_i^* (i=1, 2,... 5) and their totality forms the set C^* and determines the composition of the interregional level of the system (Fig. 1).

Thus, it can be concluded that each of the network sections as an element of the transport system is characterized by belonging to a certain structural level, the actual length of the transport routes and the total amount of cargo traffic in two opposite directions.

Table 2 shows the data characterizing the composition of the analyzed system.

Table 2

Characteristics of the territorial transport system

Designation of sets and individual elements in their composition	Characteristics of the transport system elements		
	The system level and ordinal number of the element, i	Site length, km	Total rate of freight, t/day
A^*	*local*	$l_i^{A^*}$	$q_i^{A^*}$
a_1^*	1	23	6,110
a_2^*	2	18	4,960
a_3^*	3	31	5,740
a_4^*	4	17	6,600
a_5^*	5	27	4,140
a_6^*	6	36	5,120
a_7^*	7	32	7,220
a_8^*	8	31	7,740
a_9^*	9	24	7,910
a_{10}^*	10	26	8,800
a_{11}^*	11	18	7,140
a_{12}^*	12	25	9,300
a_{13}^*	13	34	10,140
a_{14}^*	14	22	6,840
a_{15}^*	15	31	10,200
a_{16}^*	16	29	11,220
a_{17}^*	17	32	11,140
B^*	regional	$l_i^{B^*}$	$q_i^{B^*}$
b_1^*	1	33	8,100
b_2^*	2	44	8,850
b_3^*	3	61	8,260
b_4^*	4	34	10,920
b_5^*	5	45	7760
b_6^*	6	42	10,650
b_7^*	7	46	9730
C^*	interregional	$l_i^{C^*}$	$q_i^{C^*}$
c_1^*	1	67	27,200
c_2^*	2	36	26,650
c_3^*	3	30	24,150
c_4^*	4	59	23,950
c_5^*	5	63	26,340

Fig. 2 shows the relative position in the plane $q0l$ of the elements belonging to sets A^*, B^* and C^*.

However, the use of observed values of freight rate q (t/day) and distances l (km) with specified dimensions is not informative enough in the graphical representation of the system structure shown in Fig. 2. This is because when describing the system properties, it is better to use dimensionless indexes. Therefore, instead of initial sets A^*, B^* and C^* with sets of elements $a_i^*\left(l_i^{A^*}, q_i^{A^*}\right)$, $b_i^*\left(l_i^{B^*}, q_i^{B^*}\right)$, $c_i^*\left(l_i^{C^*}, q_i^{C^*}\right)$, transformed sets A, B and C with elements $a_i\left(x_i^A, y_i^A\right)$, $b_i\left(x_i^B, y_i^B\right)$, $c_i\left(x_i^C, y_i^C\right)$ will be used further with dimensionless coordinates determined as follows:

$$\begin{cases} x_i^A = \dfrac{l_i^{A^*} - l_{\min}}{l_{\max} - l_{\min}}; \\ y_i^A = \dfrac{q_i^{A^*} - q_{\min}}{q_{\max} - q_{\min}}; \end{cases} \begin{cases} x_i^B = \dfrac{l_i^{B^*} - l_{\min}}{l_{\max} - l_{\min}}; \\ y_i^B = \dfrac{q_i^{B^*} - q_{\min}}{q_{\max} - q_{\min}}; \end{cases}$$

$$\begin{cases} x_i^C = \dfrac{l_i^{C^*} - l_{\min}}{l_{\max} - l_{\min}}; \\ y_i^C = \dfrac{q_i^{C^*} - q_{\min}}{q_{\max} - q_{\min}}, \end{cases} \tag{1}$$

where $l_{\max}$ is the maximum value of the length of the transport site among all elements $l_i^{A^*}$, $l_i^{B^*}$, $l_i^{C^*}$; $l_{\min}$ is the respective minimum value; $q_{\max}$ is the maximum freight rate among all elements $q_i^{A^*}$, $q_i^{B^*}$, $q_i^{C^*}$; $q_{\min}$ is the respective minimum value of freight rate.

Elements of the set "*A*" are described by "distance" attributes because only distances can be well-defined and stable in this site and freight rates are stochastic.

The sets *B* and *C* are predictable and more stable, so they can be handled. They adequately characterize and describe the loading and functioning of the transport systems and have connections with multiple "*A*" through distances. In principle, other factors can be used also for structuring the transport system. They have a certain stable interrelationship (for example, specific costs in the set "*A*" and volumes of transportation expressed in terms of costs in sets *B* and *C*).

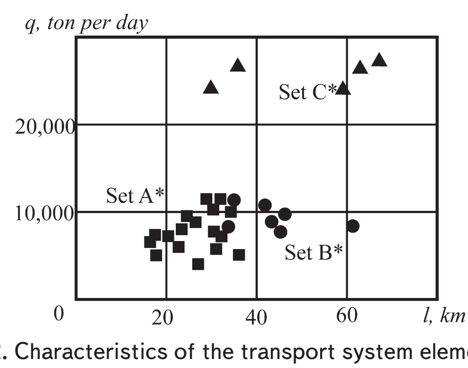


Fig. 2. Characteristics of the transport system elements as a set of points in the plane $q0l$ (where q is the freight rate; l is the length of the transportation site)

The territorial system should be considered three-level if the point elements *ai, bi, ci* belonging to different levels form non-overlapping sets *A*, *B*, and *C*. Structural analysis of such a system is connected with determining of relative position of points belonging to sets *A*, *B*, *C* in the plane $Y0X$ followed by assessment of possibility of joining overlapping sets if any.

Thus, to clarify the number of structural levels of the system and their constituent elements, criteria and algorithms must be developed to determine the relative position of these sets in the plane. Moreover, these criteria should take into account possible overlap and assessment of the necessity of further integration of overlapping sets.

Implementation of the procedure for assessing the relative proximity of the sets characterizing the structure of the transport system is an important stage of analysis. Its results will largely determine further actions related to the necessity of combining overlapping sets.

5. Development of a method for establishing the number of structural levels of the interregional transport system

The notion of distance between groups of homogeneous objects is usually used in the development of a procedure for their classification and relates to the assessment of the relative position of sets of different nature in the plane [23]. The distance determined by the principle of "close neighbor" can serve as characteristic of proximity of individual sets using potential functions, etc.

Since the center of an individual set is determined by the position of its centroid in the plane $Y0X$, the distance between the sets A and B (Fig. 3) containing respectively N_A and N_B elements is defined as the Euclidean distance between centroids S_A and S_B:

$$D_{AB} = \sqrt{\left(\overline{x}_A - \overline{x}_B\right)^2 + \left(\overline{y}_A - \overline{y}_B\right)^2} =$$

$$= \sqrt{\left(\frac{\sum_{i=1}^{N_A} x_i^A}{N_A} - \frac{\sum_{i=1}^{N_B} x_i^B}{N_B}\right)^2 + \left(\frac{\sum_{i=1}^{N_A} y_i^A}{N_A} - \frac{\sum_{i=1}^{N_B} y_i^B}{N_B}\right)^2}. \tag{2}$$

The model (2) and its elements are described in [16], namely:

– $\overline{x}_A$ and $\overline{y}_A$ are the coordinates of the S_A centroid center;

– $\overline{x}_B$ and $\overline{y}_B$ are the coordinates of the S_B centroid center;

– N_A and N_B are the numbers of points included in the centroids;

– x_i^A, y_i^A, x_i^B, y_i^B are the coordinates of points inside the centroids.

If the sets A and B are characterized by values of respective diameters D_A and D_B, such sets are assessed as non-overlapping when inequality [24] is satisfied:

$$D_{AB} < \frac{D_A}{2} + \frac{D_B}{2}$$

or, after transformations:

$$\eta_{AB} = 1 - \frac{D_A + D_B}{2D_{AB}} > 0.$$

In this case, criterion η_{AB} should be considered as an index of the pair proximity of sets A and B [25]. It assumes positive values when elements of the considered sets are distant in the $Y0X$ plane so that the areas bounded by respective diameters D_A and D_B do not overlap. In this case, gradual mutual removal of non-overlapping sets A and B will be accompanied by the continuous growth of positive values of the pair proximity index η_{AB}.

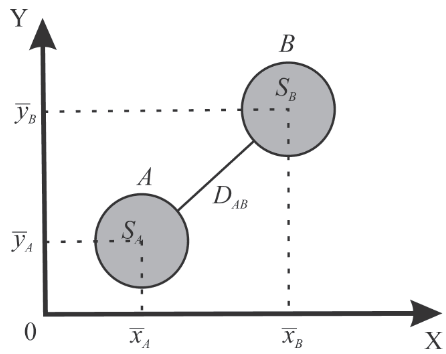


Fig. 3. Scheme of determining the Euclidean distance between sets A and B in $Y0X$ plane

If there is a partial or complete overlap of these sets in the plane, then η_{AB} assumes a negative value.

Consider now the case where three sets A, B and C are located in the $Y0X$ plane (Fig. 4) with the number of elements N_A, N_B, N_C and corresponding diameters D_A, D_B, D_C. Distance between sets A and B is determined from formula (2). Similarly, distances between the sets B and C and between C are determined.

Indexes of pair proximity for the listed sets which are determined in accordance with the outlined approach and using similar designations are determined as follows:

$$\begin{cases} \eta_{AB} = 1 - \dfrac{D_A + D_B}{2 \cdot D_{AB}}, \\ \eta_{AC} = 1 - \dfrac{D_A + D_C}{2 \cdot D_{AC}}, \\ \eta_{BC} = 1 - \dfrac{D_B + D_C}{2 \cdot D_{BC}}. \end{cases} \quad (3)$$

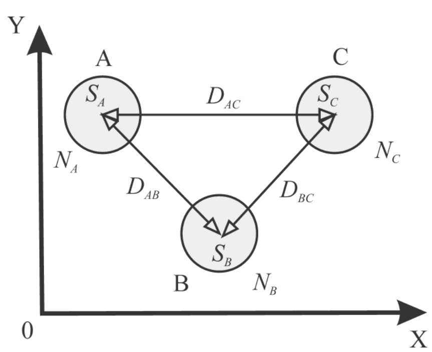


Fig. 4. Relative position of the sets A, B, C in the plane and the scheme of determining distances between them

The analyzed sets A, B and C will not overlap (Fig. 5) if the following conditions are met:

$$\begin{cases} \eta_{AB} > 0, \\ \eta_{AC} > 0, \\ \eta_{BC} > 0. \end{cases} \quad (4)$$

Note that, from a practical point of view, the situation where the analyzed system has three structural levels and the sets of corresponding point elements in the plane $Y0X$ do not overlap is of the greatest interest.

Suppose the system under analysis is three-level, and condition (4) is satisfied. Since the maximum value of each pair proximity index is equal to one, then the area of a possible change of the radius vector $\vec{\rho}$ in the system of rectangular coordinates $\eta_{AB}\ \eta_{AC}\ \eta_{BC}$ will be inside the space bounded by a unit cube (Fig. 6).

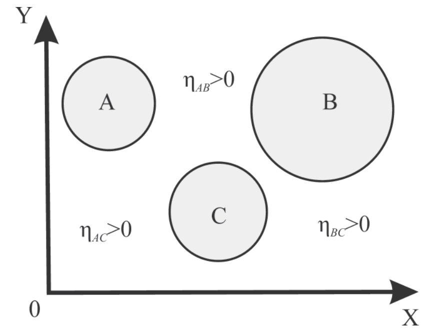


Fig. 5. Relative position of the sets A, B and C that do not overlap

Module of the radius vector $\vec{\rho}$ reaches the maximum possible magnitude in the case where the point $S^*(1,1,1)$ characterizing relative position of the sets coincides with the vertex of the cube farthest from the origin: $|\vec{\rho}|_{\max} = \sqrt{3}$ (Fig. 6)

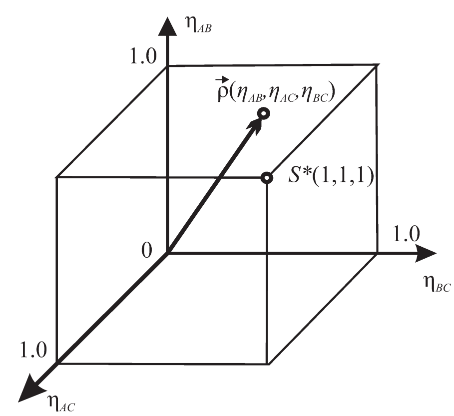


Fig. 6. Position of the radius vector $\vec{\rho}$ in the three-dimensional coordinate system of the pair proximity indexes, η_{AB}, η_{AC}, η_{BC}

This position of the radius-vector will correspond to the case of the greatest distance of all considered sets from each other. Then, to estimate the proximity of non-overlapping sets, a generalized index [24] should be used:

$$\theta = \frac{1}{\sqrt{3}} \sqrt{\eta_{AB}^2 + \eta_{AC}^2 + \eta_{BC}^2}. \quad (5)$$

The use of a normalization factor $1/\sqrt{3}$ leads to the case where the generalized proximity index can vary in the range of values $0 \le \theta \le 1$.

Thus, it can be concluded that the developed generalized index of the proximity of several non-overlapping sets is based on the consideration of pair indexes of the proximity of individual sets and is equal to their mean square value.

Note also that in the case where $\theta = 0$, there is a boundary approximation of all sets without their mutual overlap and the generalized proximity index takes negative values when there is the partial or complete overlap of any of the sets A, B, C in the $Y0X$ plane.

In general, structural features of three-level transport systems will be explicitly expressed in cases where non-overlapping sets are removed from each other so that the value of the generalized proximity index is in the range of $0.5<\theta<1.0$.

To perform calculations and assess the relative position of individual sets in the plane in accordance with the proposed algorithm and using the developed indexes in the integrated Mathcad computing system, a computer program was developed. Its possibilities were assessed for different variants of mutual arrangement of sets A, B and C.

For example, Fig. 7 shows the relative position of non-overlapping sets and coordinates of their individual elements are given in Tables 3–5.

Table 3

Coordinates of the set *A* elements

i	1	2	3	4	5	6	7	8	9
x_i	0.2	0.3	0.275	0.325	0.25	0.35	0.225	0.275	0.325
y_i	0.8	0.8	0.775	0.775	0.75	0.75	0.725	0.725	0.725
i	10	11	12	13	14	15	16	17	18
x_i	0.2	0.25	0.3	0.35	0.225	0.3	0.25	0.175	0.45
y_i	0.7	0.7	0.7	0.7	0.675	0.675	0.65	0.625	0.7

Table 4

Coordinates of the set *B* elements

i	1	2	3	4	5	6	7	8	9	10
x_i	0.551	0.475	0.491	0.595	0.45	0.471	0.485	0.53	0.551	0.555
y_i	0.4	0.375	0.375	0.375	0.35	0.35	0.35	0.325	0.3	0.3
i	11	12	13	14	15	16	17	18	19	20
x_i	0.493	0.492	0.51	0.385	0.371	0.471	0.477	0.385	0.393	0.385
y_i	0.275	0.275	0.25	0.225	0.225	0.2	0.175	0.175	0.15	0.15

Table 5

Coordinates of the set *C* elements

i	1	2	3	4	5	6	7	8	9	10
x_i	0.55	0.575	0.65	0.625	0.61	0.671	0.71	0.712	0.615	0.715
y_i	0.775	0.755	0.751	0.715	0.72	0.725	0.73	0.665	0.621	0.624

In the case under consideration, pair indexes of proximity take the following positive values:

$$\begin{cases} \eta_{AB} = 0.384, \\ \eta_{AC} = 0.302, \\ \eta_{BC} = 0.422. \end{cases}$$

Respectively, the value of the generalized proximity index $\theta = 0.373$. It is seen from Fig. 7 that the overlapping of the analyzed sets does not occur and, therefore, the system under consideration is three-level.

In the case where elements of the sets A, B and C are characterized by the data set presented in Tables 6–8, all above sets will overlap as shown in Fig. 8.

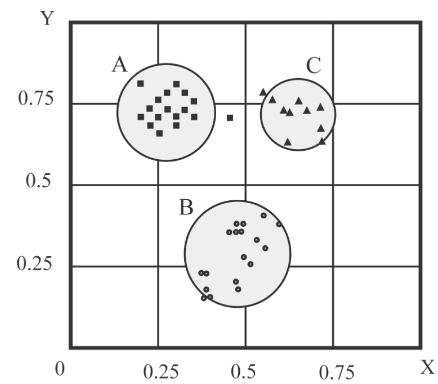


Fig. 7. Relative position of three non-overlapping sets

Table 6

Coordinates of the set *A* elements

i	1	2	3	4	5	6	7	8	9
x_i	0.4	0.5	0.475	0.525	0.45	0.55	0.425	0.475	0.525
y_i	0.8	0.8	0.775	0.775	0.75	0.75	0.725	0.725	0.725
i	10	11	12	13	14	15	16	17	18
x_i	0.4	0.45	0.5	0.55	0.425	0/5	0.45	0.375	0.65
y_i	0.7	0.7	0.7	0.7	0.675	0.675	0.65	0.625	0.7

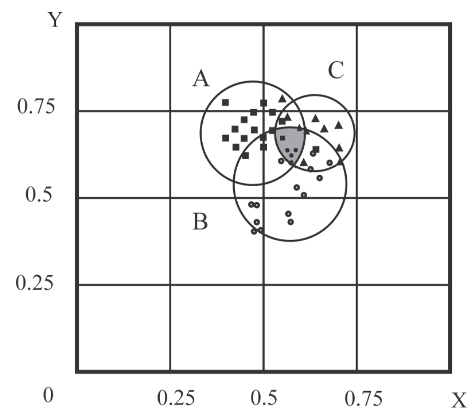


Fig. 8. Relative position of the three overlapping sets in the plane

Table 7

Coordinates of the set *B* elements

i	1	2	3	4	5	6	7	8	9	10
x_i	0.651	0.575	0.591	0.695	0.55	0.571	0.585	0.63	0.651	0.655
y_i	0.7	0.675	0.675	0.675	0.65	0.65	0.65	0.625	0.6	0.6
i	11	12	13	14	15	16	17	18	19	20
x_i	0.93	0.592	0.61	0.585	0.471	0.471	0.577	0.485	0.493	0.485
y_i	0.575	0.575	0.55	0.525	0.525	0.5	0.475	0.475	0.45	0.45

In this case, all values of the indexes of pair proximity will be negative:

$$\begin{cases} \eta_{AB} = -0.747, \\ \eta_{AC} = 0.546, \\ \eta_{BC} = 0.835. \end{cases}$$

Table 8

Coordinates of the set *C* elements

i	1	2	3	4	5	6	7	8	9	10
x_i	0.55	0.575	0.65	0.625	0.61	0.671	0.71	0.712	0.615	0.715
y_i	0.775	0.755	0.751	0.715	0.72	0.725	0.73	0.665	0.621	0.624

Thus, the developed indexes and the corresponding calculation program for assessment of the relative position of sets in a plane will make it possible to determine the expected properties of the analyzed multilevel transport systems.

6. Establishing the number of structural levels of the transport system

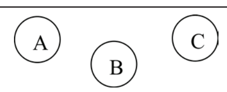
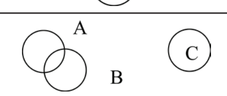
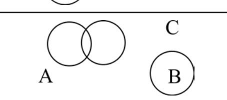
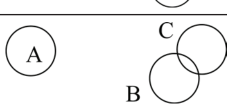
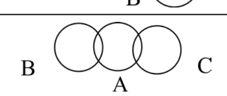
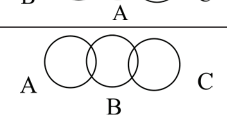
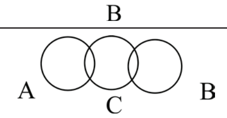
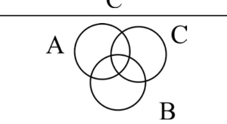
Peculiarities of territorial transport system functioning are closely related to their structure which is characterized by some combination of paired proximity indexes. However, as shown earlier, the values of individual indexes η_{AB}, η_{AC}, η_{BC} can be both positive and negative.

This means that, in the general case, there are eight variants of the combination of signs of pair proximity indexes that can be brought to conformity with structural indexes with the symbolic representation of *S*1, *S*2,..., *S*8.

The definition of the structural index of the analyzed system as its most important characteristic should be made in each case in accordance with the data presented in Table 9.

Table 9

Structural characteristics of multilevel transport systems

Symbolic representation of the structural index of the system	Scheme of relative position of individual sets in a plane	Signs of pair proximity indexes		
		η_{AB}	η_{AC}	η_{BC}
*S*1		+	+	+
*S*2		–	+	+
*S*3		+	–	+
*S*4		+	+	–
*S*5		–	–	+
*S*6		–	+	–
*S*7		+	–	–
*S*8		–	–	–

In general, we can assert that the structural index is a characteristic of a family of homogeneous transport systems with similar properties. The possible variety of structures observed in practice is described using eight basic variants corresponding to one or another structural index with symbols *S*1, *S*2,..., *S*8.

7. Discussion of the results obtained in the study of theoretical bases of transport system analysis

Practical problems related to the refinement of structure, composition and modes of operation of transport systems should be solved on the basis of a predefined structural index.

Thus, the procedure of structural analysis of the transport system is connected with the need to predetermine its structural index according to the results of the calculation of values of paired proximity indexes in conformity with the data presented in Table 9.

For each structural index, Table 10 provides information on possible variants of joining overlapping sets and the number of structural levels corresponding to variants of such joining.

Then, the number of structural levels of a functioning transport system should be determined on the basis of the following sequence of actions:

1) upon determining values of paired proximity indexes, structural index of the analyzed system is determined taking into account signs of pair proximity indexes and using the data given in Table 9;

2) within the established structural index, it is decided which of the overlapping sets should be joined and which should be considered as only partially overlapping;

3) final decision on determining the number of structural levels of the analyzed system is made after performing the procedure of joining overlapping sets in accordance with the data presented in Table 10.

It should be noted that when solving the problem of determining the number of structural levels of the system, a need appears to develop criteria and decision-making rules related to the possible joining of partially overlapping sets in the *Y*0*X* plane.

Let us take a closer look at this procedure. Suppose that two sets *W* and *V* with diameters D_W and D_V partially overlap. In this case, $D_W > D_V$, and the value of their overlap Z>0 (Fig. 9).

Define coefficients K_1 and K_2 as dimensionless relative values:

$$K_1 = \frac{D_V}{D_W}, \tag{6}$$

$$K_2 = \frac{Z}{D_V} = 0{,}5 + \frac{D_W - 2D_{WV}}{2D_V}. \tag{7}$$

Z value of partial overlapping of sets (Fig. 9)

$$Z = \frac{D_W + D_V}{2} - D_{WV}. \tag{8}$$

Since $D_W > D_V$, the coefficient is $0 < K_1 < 1$. If $0 < K_1 < 0.25$, then because of a relatively small diameter of the set *V*, we can assume that elements of the set *V* represent an "overshot" that should be included in the main set *W* regardless of the magnitude of overlap, *Z*.

Table 10

Structural indexes of systems and their corresponding variants of structure formation

<table>
<tr><td>Symbolic representation of the structural index of the system</td><td colspan="4">Number of levels of the transport system when conditions connected with partial overlapping and joining of structural element sets are met</td></tr>
<tr><td>S1</td><td colspan="4">three levels if sets A, B and C are not overlapping</td></tr>
<tr><td>S2</td><td colspan="2">two levels in presence of joined sets A&B</td><td colspan="2">three levels in partial overlapping of A and B</td></tr>
<tr><td>S3</td><td colspan="2">two levels in presence of joined sets A&C</td><td colspan="2">three levels in partial overlapping of A and C</td></tr>
<tr><td>S4</td><td colspan="2">two levels in presence of joined sets B&C</td><td colspan="2">three levels in partial overlapping of B and C</td></tr>
<tr><td>S5</td><td>one level in presence of joined sets A&B&C</td><td>two levels in presence of joined sets A&B and partial overlapping of A and C</td><td>two levels in presence of joined sets A&C and partial overlapping of A and B</td><td>three levels in partial overlapping of A and B, and A and C</td></tr>
<tr><td>S6</td><td>one level in presence of joined sets A&B&C</td><td>two levels in presence of joined sets A&B and partial overlapping of B and C</td><td>two levels in presence of joined sets B&C and partial overlapping of A and B</td><td>three levels in partial overlapping of A and B, and B and C</td></tr>
<tr><td>S7</td><td>one level in presence of joined sets A&B&C</td><td>two levels in presence of joined sets A&C and partial overlapping of C and B</td><td>two levels in presence of joined sets B&C and partial overlapping of A and C</td><td>three levels in partial overlapping of A and C, and C and B</td></tr>
<tr><td>S8</td><td colspan="4">one level in presence of joined sets A&B&C</td></tr>
</table>

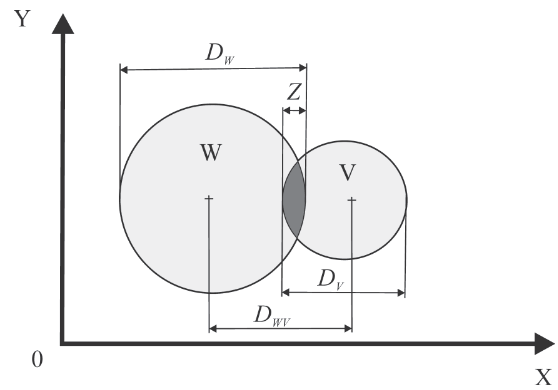


Fig. 9. Relative position of two partially overlapping sets *W* and *V* in the plane

When analyzing the possible change in the coefficient K_2 with the growth of overlap Z, it should be noted that when condition $K_2>0.5$ is met, the centroid of the set V falls within the boundary of the set W determined by a circle of diameter D_W.

For this reason, observance of inequality $K_2>0.5$ is further considered as a sufficient ground for joining partially overlapping sets W and V.

Graphical representation of the developed algorithm of joining overlapping sets is shown in Fig. 10. For the region Ω_1 of values of the coefficients K_1 and K_2, partially overlapping sets W and V should be regarded as existing separately with partial "mixing" of some of their elements.

For the area Ω_2 of values of coefficients K_1 and K_2, it is advisable to join sets W and V because of significant overlap and "mixing" of their elements.

Thus, a method of establishing the number of structural levels of the interregional transport system was developed based on preliminary determination of the structural index of the system followed by decision-making on joining the overlapping sets, if any.

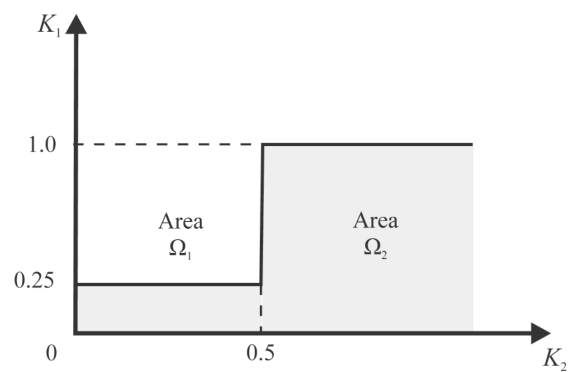


Fig. 10. Areas Ω_1 and Ω_2 of values of coefficients K_1 and K_2 for which alternative decisions are made for joining the overlapping sets

Using the developed method of structural analysis with respect to the system presented in Fig. 1, it can be shown that irrespective of partial overlap of sets A and B (Fig. 11), they should not be joined since in this case $K_1=0.70$ and $K_2=0.34$.

The calculation results make it possible to conclude that the system shown in Fig. 1 is characterized by the following set of parameters: $D_{AB}=0.341$, $D_{AC}=0.918$, $D_{BC}=0.73$, $D_A=0.391$, $D_B=0.56$, $D_C=0.752$, $\eta_{AB}=-0.393$, $\eta_{AC}=0.378$, $\eta_{BC}=0.101$ and should be considered as a three-layer system with structural index $S2$.

The study results provide new tools for analyzing and characterizing transport systems. However, there are some disadvantages to point out. In particular, the issue of taking into account the interaction of different types of transport, time and costs of overloading and cargo storage at transit warehouses remained insufficiently defined. To improve the functioning of transportation systems, these factors have to be investigated and taken into account. It is this problem that will be addressed in future studies of regional transport systems.

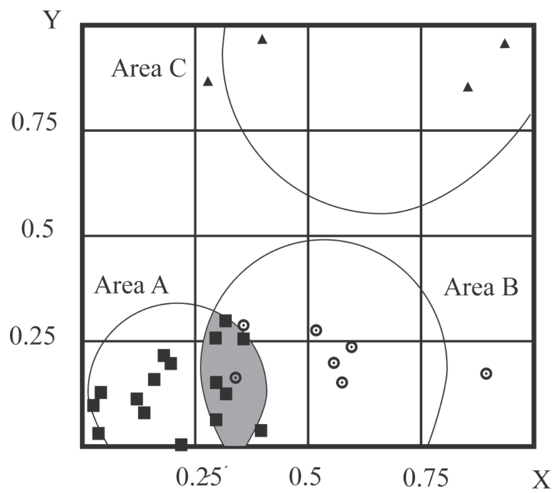


Fig. 11. Relative position of the sets *A, B, C* of elements of territorial transport system in the plane *Y0X*

8. Conclusions

1. A method of transport system decomposition for singling out individual levels based on logistical principles was developed which makes it possible to determine quantitative composition and characteristics of its individual levels. It was proved that the criteria by which transport systems are assessed are closely related to their structure. According to the developed classification, the system structure is characterized by a set of structural indexes $S1$, $S2$,..., $S8$. Systems with the same indexes and the same number of levels are structurally similar.

2. A method of determining structural indexes with the use of system integration was proposed. The procedure of structural analysis of the transport system is connected with the necessity of preliminary determination of its structural index according to the results from the calculation of values of pair proximity indexes. For each structural index, data were presented on possible variants of joining overlapping sets and information on the number of structural levels corresponding to different variants of such joining.

3. A method of establishing the number of structural levels of inter-regional transport systems was developed based on preliminary determination of the system's structural index followed by decision-making on joining overlapping sets if any. Application of the proposed method enables the structuring of transport systems while singling out individual levels and differentiation of costs of the system development and its operation in the course of the system functioning.

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