Таким образом, свойства трехуровневых межрегиональных транспортных систем в наибольшей степени проявятся именно в тех ситуациях, когда неперекрывающиеся множества в достаточной степени удалены друг от друга, а величина обобщенного показателя близости находится в интервале значений $0,5< \theta <1,0$.

ВЫВОДЫ

Предложен метод структурного анализа и определения числа структурных уровней межрегиональных транспортных систем, основанный на разделении множества их элементов на отдельные группы и с учетом отведенной им роли в транспортном процессе. Показано, что в общем случае межрегиональная транспортная система может иметь три уровня, а оптимизацию ее функционирования следует осуществлять последовательно на каждом из предусмотренных структурных уровней.

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STRUCTURAL LEVELS OF INTERREGIONAL TRANSPORT SYSTEMS

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ABSTRACT

A method for determining structural levels of interregional transport systems, algorithms and quantitative criteria to establish the composition and number of structural levels have been developed. It is shown that, in general, interregional transport system can have three levels (local, regional and interregional), and optimization of its operation should be carried out sequentially at each of these levels, taking into account proposed mathematical tools.

ENGLISH SUMMARY

Background.

Formation of transport systems, their development, infrastructure renewal and organization of optimal functioning are a set of tasks, the importance of which is closely linked with the economic development of regions and territories [1–3].

For cargo transportation between neighboring enterprises that are in productive relations and forming separate clusters, transport network of the local level is created. At the regional level centers of individual clusters are connected with means of communication with formation of a unified transport network that supports the interaction of different entities. In addition, the need for transit of goods leads to the formation of transport corridors with predominantly through freight traffic, for which appropriate conditions must be provided [4].

Hence there is a corollary: interregional transport systems may have a complex multilevel structure, and it is proposed to carry out the optimization of such systems' functioning separately at each level [5, 6].

This means that the operation of the optimization procedure must be preceded by the step of determining the number of levels of the system and identifying belonging of individual components to local, regional or interregional levels.

However, such data are not provided in scientific sources, making it difficult to conduct structural analysis and solution of task of necessary optimization. There is a need for development of a method for determining the composition and quantity of structural levels of interregional transport systems.

Objective.

The objective of the article is the study of interregional transport networks as multilevel systems and introduction of an appropriate method for its structural analysis.

Methods.

The author uses analysis and mathematical method.

Results.

Elements and levels

A fragment of interregional transport system (shown in Pic. 1.) is taken for an analysis. Components of this structure are means of communication, which are used for freight delivery and united in a general network with the help of transport junctions.

Generally, the elements of the system can be divided into separate groups based on the role they play in the transport process.

They can be: local level, defined by the set of elements for the operation of individual clusters as a set of interrelated enterprises and industries in the relevant territory; regional – defined by the set of transport routes connecting the centers of individual clusters in a single transport network; interregional –

as a set of interregional highway sections, the operation of which is associated with movement of transit traffic flows.

In addition, each of the existing sections of the transport network, being an element of interregional system, is characterized by:

– Belonging to one of three designated levels;

– Length (actual distance between transport junctions, which determine its position);

– The value of cargo flow, which is the total amount of freight traffic during the analyzed time period at the section under consideration in both directions.

To denote components of transport system the following symbols are used: a_i^* (i=1, 2, ... N_A) for local level, b_i^* (i=1, 2, ... N_B) for regional level, c_i^* (i=1, 2, ... N_C) for interregional level. Total of all elements a_i^* forms a set A*, which characterizes local level of the system, total of all elements b_i^* forms a set B*, representing regional level, and elements c_i^* is a set C* and interregional level (Pic. 1).

Since each component of the sets is characterized by the length l and the volume of freight flow q under consideration, these characteristics must be regarded as the coordinates of these elements the plane q0l.

Then the structure of interregional transport network can be described with a set of elements (points on a panel):

$$\begin{cases} a_i^*(l_i^{A*}, q_i^{A*}) & (i = 1, 2, \dots N_A) \\ b_i^*(l_i^{B*}, q_i^{B*}) & (i = 1, 2, \dots N_B) \\ c_i^*(l_i^{C*}, q_i^{C*}) & (i = 1, 2, \dots N_C), \end{cases}$$

where $N_A+N_B+N_C$ – total number of system's elements and the total amount of all transport routes.

Then for a fragment of interregional transport system, shown in Pic.1, total amount of transport routes: $N_A+N_B+N_C = 32$ (Table 1).

The data in Table 1 were used in the construction of the set of points belonging to the sets A *, B * and C * in the coordinate system q0l (Pic. 2). The figure shows that the analyzed fragment has three groups of nearby points, confirming the existence of three structural levels in the system.

However, in general, to determine the number of structural levels and subsequent decision-making related to the optimization of transport system operation, some graphic constructions are not enough.

Solution of this problem is related to the need to establish quantitative criteria and the corresponding calculation algorithms that will make it possible to give up on a visual estimation of the mutual location on the plane elements of the sets A *, B * and C *. Development of criteria should be performed after converting the original data based on the use of variables q [t / d] and l [km] with the specified dimension to the dimensionless parameters. Coordinates of the elements belonging to the set A *, should be converted:

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

In the same way coordinates of elements of the set B* are transformed:

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

Thus, for elements of the set C*:

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

where $l_{\max}$ – the maximum length of the transport section among all elements, belonging to the sets A*, B* and C*;

$l_{\min}$ – the smallest length of a transport section;

$q_{\max}$ – maximum value of general freight flow among all elements, belonging to the sets A*, B* and C*;

$q_{\min}$ – minimum value of a freight flow.

For data, shown in Table 1, values of these characteristics are: $l_{\min}$ = 33 [km], $l_{\max}$ = 181 [km], $q_{\min}$ = 2650 [t/day], $q_{\max}$ =18300 [t/day].

It should be noted that the substitution of variables leads to the fact that all elements of new sets A, B and C are located within a square with sides equal to 1. Thus, Pic.3 shows the location of the sets A, B and C in the coordinate system Y0X for transformation of the source data system. It is evident that the mutual arrangement of the elements is similar to the arrangement of elements of the initial sets A *, B * and C * on the plane q0l.

Thus a conclusion can be made that transformation of variables simplifies the evaluation of mutual arrangement of sets, characterizing the structure of the transport system. In this case non-overlapping sets A *, B * and C * will match the non-overlapping sets A, B, C in the new coordinate system Y0X.

If initial sets «are overlapped», in the coordinate system Y0X corresponding elements will be located as it is shown in Pic.4, and it will be impossible to separate them visually into individual sets A, B, C with their borders. In this case, the analyzed transport system is a single-level, and optimization of its operation should be carried out otherwise than in case of multilevel systems.

That is, the procedure of structural analysis and quantification of the levels of the transport system is associated with the need to assess relative location of the sets A, B and C in the coordinate system Y0X, taking into account the possibility of partial or complete «overlapping».

Generally, interregional transport system may include three levels; each one is characterized by a set of nearby points on the plane Y0X forming separate sets. Structure of the network should be considered as a multi-level, if analyzed sets are not overlapped, and the number of structural levels of the system is determined by the number of such sets.

Thus, the assessment of mutual arrangement of individual sets, characterizing the structure of the transport system, serves as an important step in the analysis, the results of which determine the essence of next steps, related to the optimization of its functioning.

In accordance with existing representations measure of the proximity of individual elements of the set is the distance between them, which, depending on the nature of the problem to be solved is defined in various ways [7].

Set and its characteristics

Taking a set of elements as a set of finite number of points on the plane, it is noted that the choice of the metric or measure to assess their proximity becomes an obligatory stage of the structural analysis [7].

Then proximity of elements $a_i(x_i^A, y_i^A)$ and $a_j(x_j^A, y_j^A)$, belonging to the set A, is assessed, using Euclidean distance, which is determined on the plane Y0X as follows:

$d_{i,j}^A = \sqrt{(x_i^A - x_j^A)^2 + (y_i^A - y_j^A)^2}$.

In this case proximity of individual elements coincides with their geometric proximity on the plane Y0X, and a characteristic for such a set, which includes N_A elements, is a maximum distance D_A between its points:

$$D_A = diam\ A = \sup_{x,y \in A} d(x,y)$$

Thus, in what follows the diameter of the set refers to the upper bound of the distances between pairs of its points [8]. This means that a set of elements a_i (i=1,2,... N_A) on the plane may be «transformed by» a circle with diameter D_A.The center of this circle, however, is not the center of the whole set. It happens due to the fact that when there are several elements with distances between them, which are equal to D_A, several centers appear in the set. Therefore, in general, a set of elements on the plane does not have a center.

However, in solving problems, e. g. those associated with the definition of the center of gravity of points' system centroid acts as the center of the set [9], i. e. the point S_A on the plane with coordinates:

$$\bar{x}_A = \frac{\sum_{i=1}^{N_A} x_i^A}{N_A}; \quad \bar{y}_A = \frac{\sum_{i=1}^{N_A} y_i^A}{N_A}.$$

In general, characteristics of the set have the following properties:

1. With a large number of elements (a few dozen or more) connection to a set of several points within the circle with diameter D_A centered at S_A does not lead to a noticeable change in position of the center (the stability property of the centroid location).

2. Diameter of the set does not change, if coordinate values of each of its elements increase (decrease) at the same number (the property of independence of the diameter on the location of the coordinates' origin).

3. Addition of a new element to the set increases its diameter only in the case if it is an increase in the maximum distance between the elements.

These properties allow to consider D_A, $\bar{x}_A$ and $\bar{y}_A$ as characteristics which are suitable for the description of group properties of the elements constituting the set A.

Characteristics of mutual arrangement of sets

The notion of distance between groups of similar objects is typically used in the development of classification procedure and is connected with evaluating the mutual arrangement of sets of different nature on the plane. In this as a measure of proximity of individual sets can serve distance determined by the principle of «near neighbor» using potential functions, etc.

Since the center of an individual set is determined by the location of a centroid on the plane Y0X, distance between sets A and B, which contain respectively N_A and N_B elements, is defined as Euclidean distance between centroids S_A and S_B (Pic. 5):

$$D_{AB} = \sqrt{(\bar{x}_A - \bar{x}_B)^2 + (\bar{y}_A - \bar{y}_B)^2} = \sqrt{\left[\frac{\sum_{i=1}^{N_A} x_i^A}{N_A} - \frac{\sum_{i=1}^{N_B} x_i^B}{N_B}\right]^2 + \left[\frac{\sum_{i=1}^{N_A} y_i^A}{N_A} - \frac{\sum_{i=1}^{N_B} y_i^B}{N_B}\right]^2}. \quad (1)$$

If sets A and B are characterized by values of diameters D_A and D_B, then in the following such sets are assessed as non-overlapping in case when

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

After transformations this condition is:

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

In this case the criterion η_{AB} should be evaluated as an indicator of pair proximity of sets A and B. It obtains positive values, if sets are remote on the plane Y0X and «mixing» of their elements does not occur. Otherwise $\eta \le 0$. At the same time gradual mutual increase in distance between non-overlapping sets A and B will be accompanied by the continuous growth of positive values η_{AB} .

For example, on the plane Y0X (Pic. 6) there are three sets A, B and C with the number of elements N_A, N_B, N_C and diameters D_A, D_B, D_C respectively.

Distance between sets A and B is fixed by the formula (1). In the similar way, distances between sets B and C, as well as A and C are determined.

Indicators of pair proximity of sets are determined as:

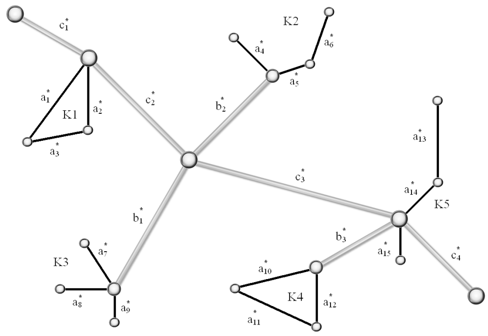
$$\begin{cases} \eta_{AB} = 1 - \frac{D_A + D_B}{2 \cdot D_{AB}} \\ \eta_{AC} = 1 - \frac{D_A + D_C}{2 \cdot D_{AC}} \\ \eta_{BC} = 1 - \frac{D_B + D_C}{2 \cdot D_{BC}}. \end{cases}$$

Analyzed sets A, B and C will not be overlapped, if the following condition is met:

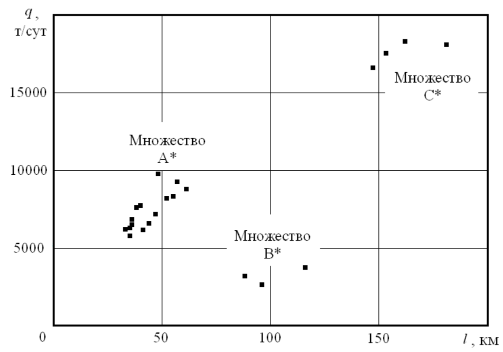
$$\begin{cases} \eta_{AB} > 0 \\ \eta_{AC} > 0 \\ \eta_{BC} > 0. \end{cases} \quad (2)$$

From a practical viewpoint, this situation is the most interesting, since the analyzed system has three structural levels (local, regional and inter-regional).

For example, it is assumed that the system has three levels and condition (2) is met. Since maximum permissible value of a pair indicator is equal to 1, in the rectangular coordinate system (η_{AB}, η_{AC}, η_{BC}) area of repositioning of the radius vector $\vec{\rho}$ will be within the space, limited by the unit cube (Pic. 7).



Pic. 1. Fragment of an interregional transport system, uniting productive clusters K1, K2,… K5.



Pic. 2. Representation of a set of transport system's elements as group of points on the plane q0l.

Module of radius- vector $\vec{\rho}$ reaches a maximum possible value, when point S^*, characterizing mutual arrangement of sets (Pic. 7), coincides with the vertex of the cube, which is the remotest of the origin of coordinates:

$$|\vec{\rho}|_{\max} = \sqrt{3}.$$

Such a position of the radius vector corresponds to maximum remoteness of all sets from each other. And here to assess mutual proximity of three analyzed sets complex factor θ is applied:

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

Application of normalization factor $1/\sqrt{3}$ leads to the fact that complex factor of proximity can change in the range $0 \le \theta \le 1$.

Therefore, it can be concluded that the developed complex factor of proximity of several non-overlapping sets is based on accounting of pair indicators of proximity of individual sets and equal to their root mean square.

For example, we take into account that the value $\theta = 0$ corresponds to the case of the highest proximity of all sets without mutual overlapping. Value $\theta = 1$ corresponds to the case of mutual remoteness of sets in the maximum possible distance. At the same time as sets on the plane Y0X become mutually remote, there will be a continuous growth of corresponding values θ.

Thus, the properties of three-level interregional transport systems manifest to the greatest extent in those situations where non-overlapping sets are sufficiently distant from each other, and the value of the complex factor of proximity is in the range $0{,}5 < \theta < 1{,}0$.

Conclusion. *Method of structural analysis and determination of structural levels' numbers of interregional transport systems is proposed, which is based on separation of sets of their elements into individual groups with account of their role in transport process. It is shown that, in general, interregional transport system can have three levels and optimization of its operation should be carried out sequentially at each of the available structural levels.*

Keywords: transport, system, components, structure, interregional level, clusters, structural analysis, method, optimization.

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