Structural analysis of an interregional transport network and assessment of capability for its multi-level optimization

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S u m m a r y. We have presented the results of the structural analysis of a interregional multi-level transport system. We have proved that generally speaking, a transport network can consist of three levels, including separate clusters at the local level, groups of interconnected clusters at the regional level and clusters tied together in transit corridors at the interregional level. We have generated the criteria and the method to determine the number of levels in the transport system, which is necessary for subsequent multi-parameter performance optimization of the entire system.

K e y w o r d s. Transport, systems, optimization, structural level, cluster, transit hub, corridor.

INTRODUCTION

In terms of economic activity, individual territories and regions are interconnected through transport networks ensuring the satisfaction of emerging transportation needs [1, 2, 8, 21, 24].

This is the transport network that connects individual economic agents, and the possibility of their interaction while implementing production processes creates the necessary prerequisites for the comprehensive development of territories and economic regions.

The task of forming the rational structure of the transport network at the regional and interregional levels in these circumstances is important and urgent [5, 7, 12, 15, 16].

This is due primarily to the fact that the construction of transport communications, infrastructure facilities, their repair and maintenance, are quite expensive, and the poor quality of roads leads to increase in terms of delivery of goods, increased wear of vehicles, increased fuel consumption, environmental degradation in regions, etc. [3, 9, 13, 14, 22].

OBJECT OF RESEARCH

This paper's object of research is interregional transport systems with complex network structures. A structural analysis of such systems is carried out based on the assumption that the investigated objects are multi-leveled and characterized by the following sequence of features.

1. Economic activities of local businesses lead to the localization of production transport flows mainly at the local level within individual clusters, and the amount of transport work carried out within the boundaries of individual clusters is at least two-thirds of the total volume of the work performed by local businesses.

2. Cargo transit transportation is carried out mainly through transit corridors performing a connecting role in the interregional transport system. In this case, the transport flows, which pass through interregional transport hubs (Fig. 1), are the transit ones, and their share in the total volume of traffic between such hubs is at least two-thirds.

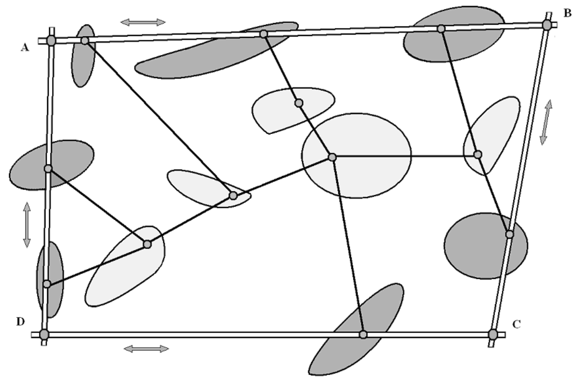

Fig. 1. Fragment of the interregional transport network bounded by hubs A, B, C, D and four transit corridors: A, B, C, D – transit transport hubs, AB, BC, CD, AD – transit corridors

If the above conditions are met, the network structure in question can be considered as multi-leveled, and the performance optimization of such transport system shall be carried out sequentially at each structural level established.

The presence of the above features of multi-level systems allows to decompose network structures and optimize the performance of systems at local, regional and interregional levels, while implementing their structural analysis [4, 6, 10].

In this case, there is a need for a consistent solution of problems related to the definition of:

- boundaries and structural components of individual clusters, within which the basic transport operation shall be carried out at the local level,
- procedure for the connection of transport hubs of individual clusters located far from transit corridors and the formation of relevant groups of clusters at the regional level,
- routes of vehicles while managing the operation of transit corridors,
- possibility of forming a unified transport network with an efficient mechanism for resolving transport issues at each system structural level established.

This approach allows to carry out multi-parameter optimization of structurally complex transport systems, thus ensuring their effective operation [17, 19, 23].

RESEARCH RESULTS

To assess the properties of the interregional transport network in accordance with the scheme proposed, we shall consider its fragment bounded by four transit corridors containing four transit transport hubs and presented in Fig. 1.

Distinctive features of the analyzed fragment are as follows:

- the presence of four transit corridors, for which transport flows passing through transit hubs are determinative, and the transit share in the total volume of traffic along the corridors is at least two-thirds,
- clusters, included in the interregional network, are located along transit corridors, and their territory is used while managing the movement of transit flows,
- located away from transit corridors, a group of clusters is characterized by the fact that the basic scope of transportation work (at least two-thirds of the total scope) at the local level is carried out within them, and the transit component is negligible and can be ignored while carrying out further analysis.

The cargo flow shall hereinafter mean the amount of cargo (in tons) carried in a given direction for a given period of time (e.g., one year) [11, 18, 20].

The cargo flow within the individual cluster, directed from the point i to the point j, is characterized by the value $q_{i,j}^{A}$. The cargo flow between the centers of clusters i and j is indicated by $l_{i,j}^{B}$. Accordingly, the flow between points i and j of the transit corridor is indicated by $q_{i,j}^{C}$.

In case the issue of forming the fragment in question is resolved correctly, the coordinate system q0l (Fig. 2) can be divided into three areas A*, B* and C* as a cluster of groups of points characterizing the presence of three structural levels.

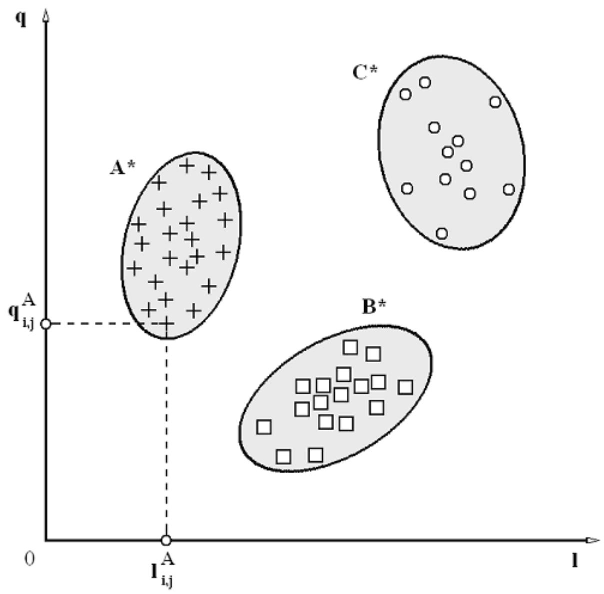

Fig. 2. Relative positions of the areas A*, B* and C*, characterizing the cluster of points in the coordinate system q0l

The group of points belonging to a particular set shall hereinafter mean a cluster of a finite number of homogeneous elements with common characteristics.

With regard to the issue in question, the points belonging to the area A* form a set characterizing transport routes, relatively short in length $l^A_{i,j}$, within individual clusters, where local transportation, characterized by cargo flows $q^A_{i,j}$, is carried out.

Area B* comprises a group of points characterizing transport routes of a greater length between the individual clusters $l^B_{i,j}$, with less regional traffic volumes, compared to the previous case, and cargo flows $q^B_{i,j}$ relevant to them.

Area C* comprises a group of points characterizing cargo flows $q^C_{i,j}$ along existing transit corridors with the appropriate length $l^C_{i,j}$.

In case of separate location of areas A*, B* and C* on the plane q0l, we shall assume that the predefined principles of forming a multi-level transport network are implemented in practical work, and the capability to ensure the optimal functioning of the entire system should be seen as achievable.

If the decisions made in connection with the definition of the boundaries of clusters and further formation of the transport network are unsuccessful or faulty, then the areas A*, B* and C* will be partially or completely overlapped in the coordinate system q0l (Fig. 3).

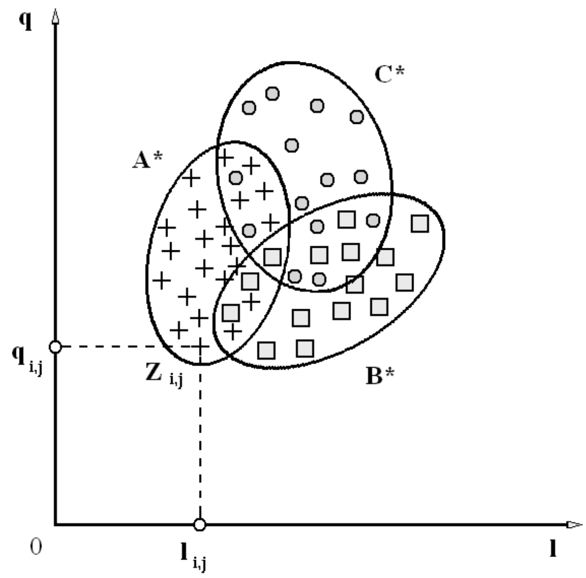

Fig. 3. Relative positions of overlapping areas A*, B* and C* in case of synthesis of the transport network with unsatisfactory properties

This means that the decisions made in connection with the formation of clusters, location selection of transport hubs and their gathering, construction of transport corridors, should be clarified or corrected.

Thus, in accordance with the proposed approach, the appropriateness of certain decisions related to the formation of the interregional transport network at different structural levels can be assessed using the appropriate graphical representations in the coordinate system q0l.

And the appearance of the areas covering certain sets gives an idea of the structure of the analyzed transport network.

However, a disadvantage of the proposed approach is that all the graphical representations are made using the dimensional quantities q and l. To increase the obviousness of the results and to create conditions for the development an appropriate computer program, one shall first convert the raw data. For example, sets within the boundaries of the areas A*, B* and C* (Fig. 2) formed with the use of quantities q [tpd] and l [km] with the specified dimension, shall be converted into dimensionless characteristics through the use of new variables.

These conversions for the elements of the set A* are performed using connections (1) and (2):

$$x_i^A = \frac{l_i^{A^*} - l_{\min}}{l_{\max} - l_{\min}}, \tag{1}$$

$$y_i^A = \frac{q_i^{A^*} - q_{\min}}{q_{\max} - q_{\min}}, \tag{2}$$

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

$l_{\min}$ – the respective minimum value,

l_i^A – the length of the transport route for the element i of the set A*,

$q_{\max}$ – the maximum value of cargo flow among all the elements belonging to the analyzed sets,

$q_{\min}$ – the respective minimum value,

q_i^A – the value of cargo flow for the element i of the set A*.

Using similar connections, a transition to dimensionless coordinates is carried out for all the elements of the sets B* and C*.

The procedure for change of variables, generally considered by us, leads to the fact that all the elements of the new sets A, B and C are located within a square with a side equal to one (Fig. 4).

In this case, the initial divided sets A*, B* and C* will be matched by the divided sets A, B, C, in the new coordinate system Y0X.

In Fig. 4, the approximate boundaries of these sets are represented by solid lines.

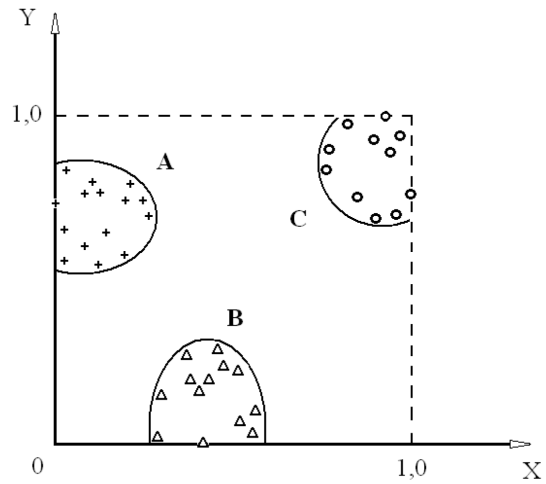

Fig. 4. Relative positions of sets of elements belonging to the divided areas A, B and C

In case the initial sets A*, B* and C* are overlapped, the corresponding elements shall be arranged in the new coordinate system Y0X as shown in Fig. 5, and it shall not be possible to visually divide them into separate sets A, B, and C with their boundaries.

Thus, the further analysis is connected with the assessment of the relative positions of the sets A, B, C, and determining the nature of their partial or complete overlap in the coordinate system Y0X.

If there is no overlap of the three areas, then the system is three-leveled, and its performance optimization shall be done for each of these levels separately.

If two of the three areas overlap, such system is two-leveled, and its performance optimization shall be carried out at the levels established.

In case where there is an overlap of the three areas, as shown in Fig. 5, the system is single-leveled, and its performance optimization shall be carried out accordingly.

Thereby, the evaluation for mutual proximity of sets, characterizing the structure of transport system, is important for analysis, the results of which determine the nature of future actions, related with optimization of system functionality.

In accordance with existing ideas, the measure of proximity for each of the elements of the set is the distance between them, which can be determined differently according to the nature of task at hand.

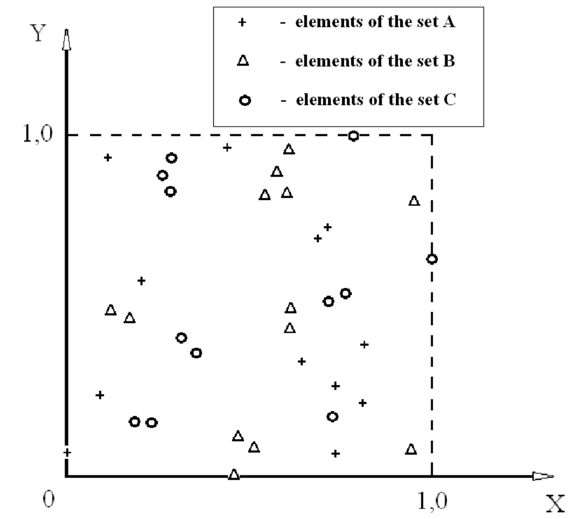

Fig. 5. Relative positions of sets of elements belonging to overlapping areas A, B and C

The choice of metric or measure, that allows evaluating the proximity of elements, which belong to one set, is very important for conducting future analysis. In common case, the measure of proximity for elements is the distance, which can be determined differently. For example, it can be Hamming distance, "balanced" Euclidean distance, distance, which is determined with the help of potential functions and so on.

Further on the proximity for elements $A_i(x_i, y_i)$ and $A_j(x_j, y_j)$ will be evaluated with the help of Euclidean distance d, which is determined on the plane Y0X this way:

$$d^{(E)}(A_i, A_j) = d\left[A_i(x_i, y_i), A_j(x_j, y_j)\right] = d_{i,j}^{A} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}\,.$$

In this case the concept of proximity for each element of the set matches with their geometrical proximity on the plane Y0X, and characteristic as a set of N_A elements, depending on the nature of task at hand, can be the diameter of the set D_A, determined, as the biggest distance between elements or average distance between all the elements of the set:

$$D_A = \frac{\sum_{i=1}^{N_A} \sum_{j=1}^{N_A} d_{i,j}^{A}}{N_A(N_A - 1)}\,.$$

If for determining of diameter for the set, we are using formula (3), we can say that value of D_A, which is the characteristic for whole set, is in the range of $dmin \le D_A \le dmax$,

where: dmin – is minimal Euclidean distance between elements of the set,

dmax – respectively, maximal Euclidean distance between elements of the set.

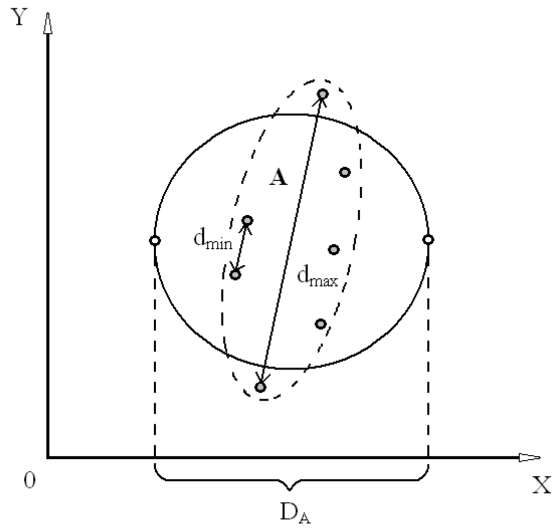

Fig. 6. Set of seven elements and graphical representation of determined characteristics dmin, dmax and D_A

It is easy to show, that if you will place a circle with the diameter of D_A in the "center" of the set A on the plane Y0X, this circle wouldn't be able to "cover" all the elements of the set, and outside of it boundaries will be at least one element (Fig. 7).

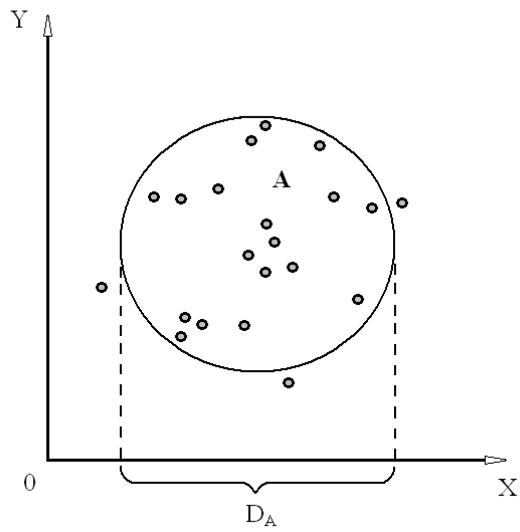

Fig. 7. Position of elements of the set A and the circle with the diameter D_A

This includes the possibility of situation, when circle with diameter D_A, which is situated in the "center" of set A does not contain any element (Fig. 8).

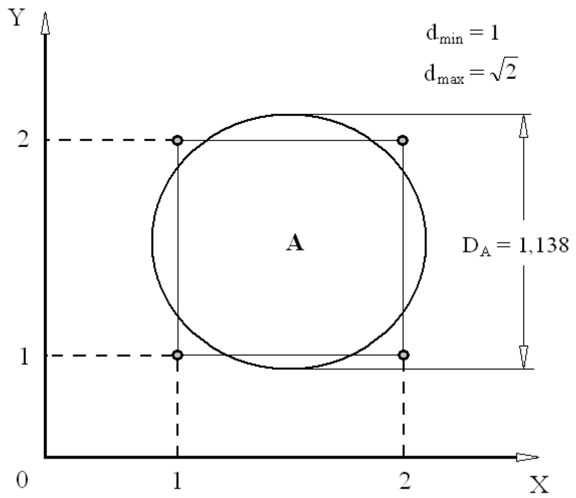

Fig. 8. Position of the four elements of the set A, which are situated outside the circle with diameter D_A.

Thus we can conclude that, regardless of the method for determining the diameter of the set, the value of D_A must be seen, as characteristic for the size of round area, in boundaries, or in close proximity of which are situated the elements of this set.

The concept of distance between groups of similar objects, usually used in development of procedure for their classification, and is related to evaluation for relative position of sets with different natures. Thus the measure of proximity for different sets can be a distance, determined using "close neighbor" rule, between "the centers of gravity", using potential function and so on.

Generalized (according to Kolmogorov) distance between sets A and B is calculated using next relation:

$$D_\tau^{(K)}(A,B) = \left\{ \frac{1}{N_A \cdot N_B} \sum_{i=1}^{N_A} \sum_{j=1}^{N_B} \left[d^{(E)}(A_i, B_j) \right]^\tau \right\}^{\frac{1}{\tau}},$$

where: N_A and N_B – quantity of elements, which analyzed sets A and B contain,

τ – some numerical parameter, chosen depending on the nature of task at hand.

In the process of future analysis we take $\tau = 2$, and distance between sets A and B can be determined using "average connection" rule, i.e. as average distance between sets, in term of arithmetic mean for all possible pair wise distances between elements of sets under consideration. Then distance D_{AB} between analyzed sets is:

$$D_{AB} = D_{\tau=2}^{(K)}(A,B) = \frac{\sum_{i=1}^{N_A} \sum_{j=1}^{N_B} d_{i,j}^{A,B}}{N_A \cdot N_B},$$

where: $d_{i,j}^{A,B}$ - Euclidean distance between elements A_i and B_j of sets A and B respectively.

For elements of sets A and B, situated on the plane Y0X, distance is determined this way (Fig. 9):

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

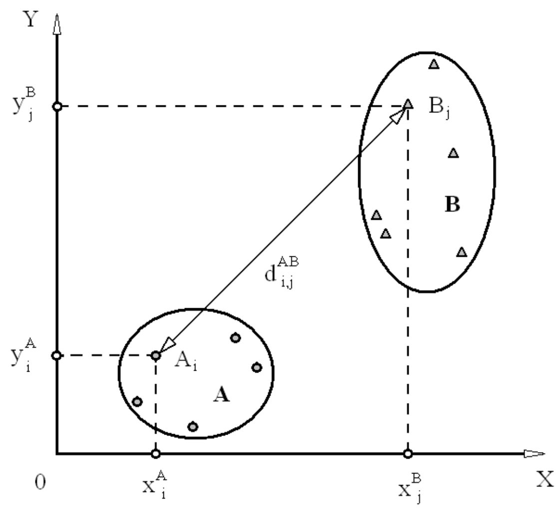

Fig. 9. Determining distance between individual elements of sets A and B

Obtained dependencies for determining D_{AB}, D_{AC}, D_{BC} can be used for determining the relative position of individual sets and structural properties for multi-level transport systems (Fig. 10).

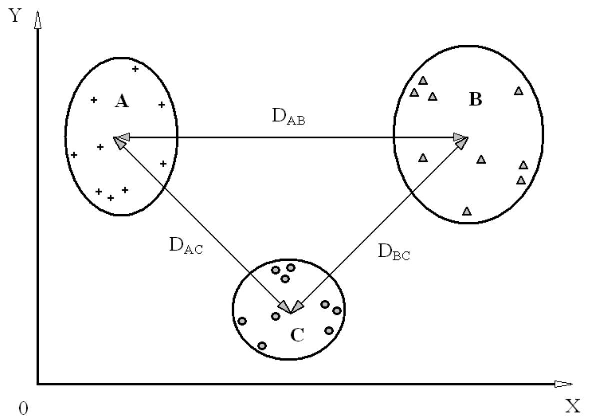

Fig. 10. Relative position of sets A, B and C on the plane Y0X

It should be noted, that from practical point of view the most interesting is situation, when analyzed system has three structural levels (local, regional and interregional), and sets of respective elements on the plane Y0X is not mixed. In this case the use of criteria D_A, D_B, D_C, D_{AB}, D_{AC}, D_{BC} allows us to determine the number of levels for interregional transport system and justify on this basis, used methods for optimization of their functionality.

CONCLUSIONS

1. We have developed a method for the structural analysis of interregional transport systems, based on the determination of their individual levels for the subsequent multi-parameter performance optimization.

2. We have proposed to present the analysis results in graph form, and thus evaluate the properties of the interregional transport systems analyzed and the capability to optimize their performance.

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СТРУКТУРНЫЙ АНАЛИЗ МЕЖРЕГИОНАЛЬНОЙ ТРАНСПОРТНОЙ СЕТИ И ОЦЕНКА ВОЗМОЖНОСТИ ЕЁ МНОГОУРОВНЕВОЙ ОПТИМИЗАЦИИ

Максим Слободянюк, Игорь Тарарычкин, Григорий Нечаев

Аннотация. Представлены результаты структурного анализа межрегиональной многоуровневой транспортной системы. Показано, что в общем случае транспортная сеть может быть трехуровневой, включая отдельные кластеры на местном уровне, группы взаимосвязанных кластеров на региональном уровне и кластеры, связанные в транзитные коридоры на межрегиональном уровне. Сформулированы критерии и метод, позволяющий определять число уровней в транспортной системе, что необходимо для выполнения последующей многопараметрической оптимизации функционирования всей системы.

Ключевые слова. Транспорт, системы, оптимизация, структурный уровень, кластер, транзитный узел, коридор.